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THESIS

Modeling of a Full Vision System Using
Combined Visual/Haptic Search
for Remote Object Identification

by

David L. Klein

December 1992

Thesis Advisor: Morris R. Driels

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Modeling of a Full Vision System Using Combined Visual Haptic Search for Remote Object Identification

by

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B.A., Mathematics, University of Illinois, 1983

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

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December 1992

ABSTRACT

It is proposed that a hybrid sensory feedback system comprising a visual peripheral component together with a haptic component corresponding to that of visual foveal information, is equivalent to that of full visual sensory feedback. Such a system is constructed and the ability of subjects to perceive objects using it is investigated by observing and classifying their search strategy. Although the provision of a peripheral component provides advantages over a purely haptic system, it is concluded that subjects rely heavily on the haptic data, and the resulting hybrid system is not equivalent to full vision.

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I. INTRODUCTION

A. REMOTELY OPERATED VEHICLES (ROV)

1. Background

ROVs are utilized to conduct underwater tasks where it is necessary or preferable to avoid human presence. Such tasks usually revolve around situations in hazardous or dangerous environments. ROVs have found wide use in the off shore industry, and to a lesser extent, in the military and scientific research communities. Applications of ROVs include inspection, monitoring, survey, search, identification, retrieval. Four classes of ROVs have been identified; tethered vehicles, free swimming vehicles, bottom crawling vehicles, and untethered vehicles. Figure 1 shows an example of a tethered ROV with a manipulator arm. While ROVs provide a significant increase in capabilities over a diver in terms of greater operating range, increased time on station, and human safety, the manipulator's inability to provide detailed haptic, or touch, input, creates difficulty for the manipulator operator in performing dextrous tasks. Further, underwater tasks are frequently performed in reduced visibility, thereby limiting object recognition ability. This lack of detailed haptic input in ROV manipulators is contrasted with a human diver's highly developed sense of touch that enables a diver to perform complicated manipulative tasks in the absence of visual input. This situation creates the likelihood that future generations of ROVs, which will be heavily reliant on visual feedback, may not offer the most efficient sensory feedback capabilities for telemanipulator operation.

2. Planned Developments

Future ROV developments rely on the concept of telepresence for manipulator operation. Sensory inputs allow the operator to "feel as if he were actually present at the remote location." (Beierl, 1991, p.4) A conceptual example of a future generation ROV teleoperation system is shown in Figure 2. The system is comprised of a master control station with a position-sensing, force-reflective controller for the remote station. The remote station consists of a manipulator subsystem involving a head, torso, and two arms. Hands are mounted on the arms, and consist of a wrist, thumb, and at least two fingers.

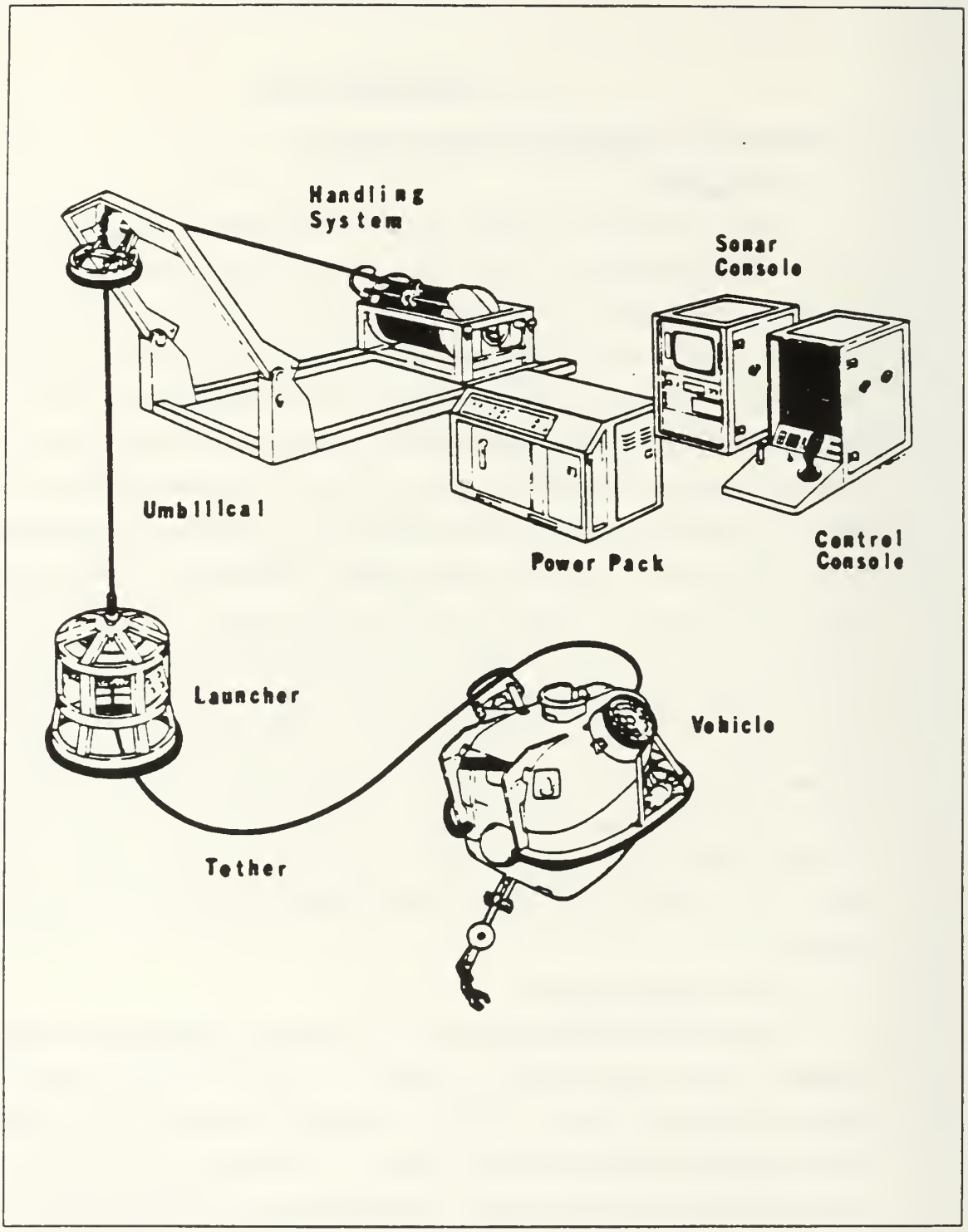


Figure 1. Remotely Operated Vehicle (Beierl,1991,p.3)

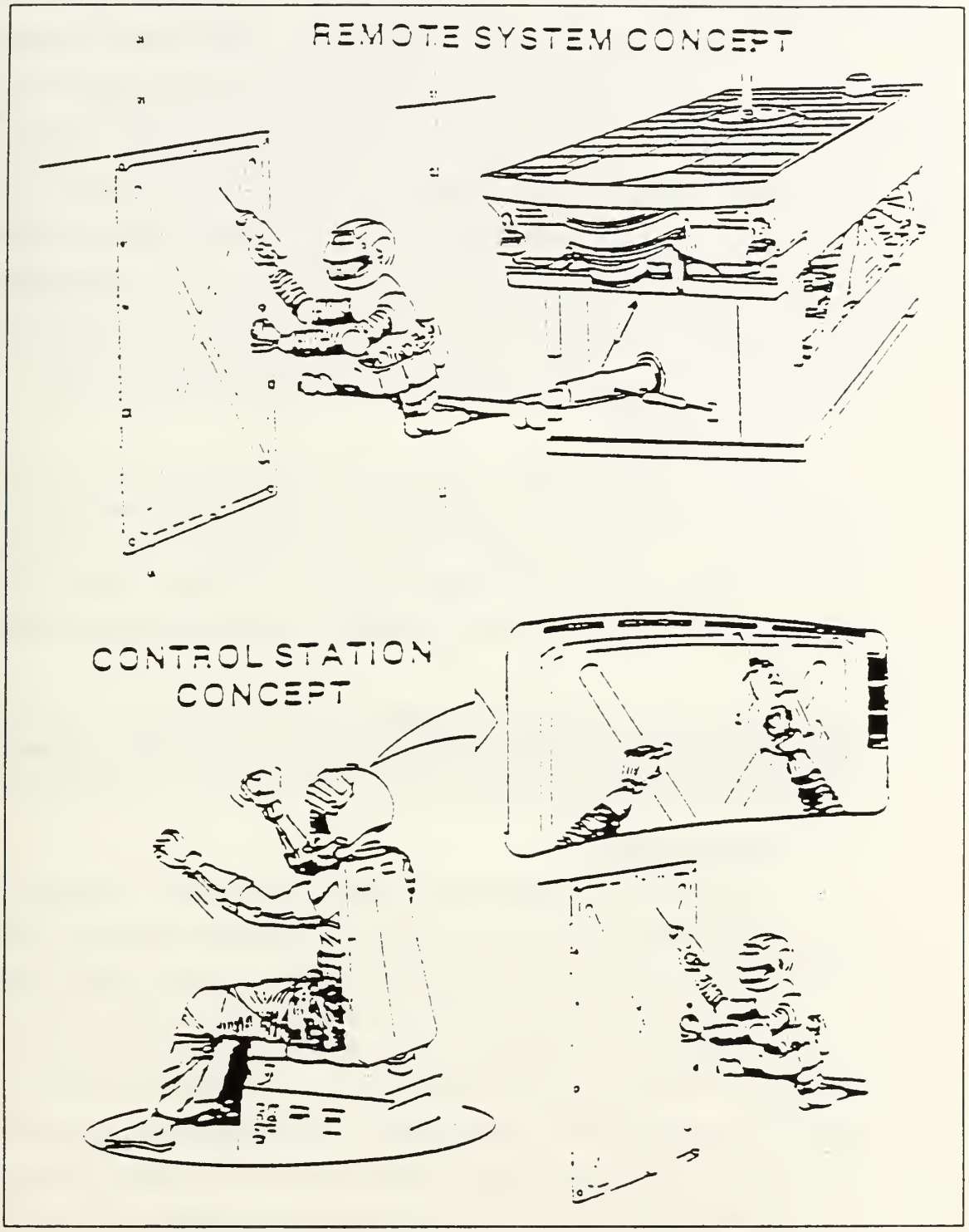


Figure 2. Conceptual Teleoperation System (Beierl, 1991, p.5)

B. TELEOPERATION

Teleoperation requires various interdependent components that provide self-locomotion, communication capabilities, and the ability to interject human presence into the area of interest. To study in detail the separate functions required to perform these tasks, teleoperation can be broken down into functional categories. Among these subsystems are the actuator, control, communication, structural, and sensor. It is the sensor subsystem which allows the man-machine interface permitting human intervention to be projected into a remote workspace. While human sensory receptors include the five traditional senses, as well as heat detection and balance, manipulator sensors are primarily dedicated to visual, acoustic, and haptic. Each of these has its own unique capabilities and problem areas associated with underwater manipulator work.

1. Visual Sensing

Most teleoperators allow for direct vision by the human operators. For optimum interface, this requires sufficient lighting, a problem in most underwater work due to the absence of a light source other than on the manipulator, and the presence of particulate matter in the water that causes light waves to scatter. The construction of a viewing system calls into question several factors concerning lighting and manipulator placement.

> Air Force studies have shown ... the distance from the manipulator operator's unaided eyes to the work should not be greater than about 10 feet. As distance increases, visual resolution and depth perception drop off and task performance time rises. (Johnsen, 1971, p.151)

2. Acoustic Sensing

A sound sensory channel offers a supplemental source of information not always available through a vision system. Sonar provides distance, speed, and directional knowledge about an object in water conditions that would render a sight system unusable. An imaging sonar, substituting ultrasonic sound for light, is analogous to television. This type of system locates the object of interest by means of a sound transducer. Reflected sound waves are captured by hydrophones and processed into electronic signals capable of being turned into a visual image. The main limitations are the poor image resolution due to the large wavelength of sound waves, and the short working distances due to the rapid attenuation of sound waves in seawater. (Johnsen, 1971, pp.158-159)

3. Haptic Sensing

In spite of the presence of other sensory inputs, human divers are known to receive the most information through their sense of touch. This is known as the haptic

sense, which consists of the divers' tactile sense - feedback generated by contact with an object - and knowledge gained through the body's position and orientation, known as kinesthesis. The ability of an ROV operator to duplicate this level of information gathering sensitivity is dependent on both the type and composition of the manipulator. Terminus type feedback is transmitted from the end effector and allows the operator to only sense an object or constraint located at the end of the manipulator. More complex, anthropomorphic man-machine interfaces allow force transmission which result from the orientation of the manipulator. Structural characteristics of the manipulator such as rigidity, friction, inertia, and size, also reduce the degree of sensitivity of the manipulator as compared to a human hand arm.

II. THEORY

The human ability to recognize and identify an object is dependent upon an interwoven network of information provided by the five senses. This information is collected through external stimulus from the surrounding environment and combined with internal body sensations such as balance, orientation, and equilibrium. The complexities involved in understanding this highly individualistic process combines both the "science" of physiology and the "art" of psychology. External sensory stimulus produces a mental image which is compared with a known internal image from the human memory. Comparison of the differences between the perceived and known images is the recognition process.

A. VISUAL RECOGNITION

Most research into human perception and recognition has focused on visual observation. Sight begins when reflected light waves from a viewed object pass through the cornea, the thin transparent tissue which acts as the eye's fixed outer lens. The cornea bends the light waves which then pass through the iris, the shutter-like device which controls the amount of light that enters the pupil. The last stage of focusing is accomplished by the bending of the light waves through a crystalline lens located behind the iris. The light waves then fall on the retina, a thin sheet of neural tissue at the back of the eye over which the image is displayed. Lying in the center of the macula (the yellow spot of the retina) is the fovea, which contains a highly concentrated array of photoreceptor cells. It is the foveal vision component which provides the narrow, central field of focused vision. Detailed visual information is received only through the narrow (1-2°) fovea, therefore the eye must scan the object (unless it subtends only a very small angle of the visual field) in order to provide information. These eye movements are called saccades and occur very rapidly while accounting for only 10% of the viewing time. "During normal viewing of stationary objects, the eye alternates between fixations ... and rapid movements called saccades". (Noton and Stark, 1971, p.34)

Since the fovea encompasses such a limited range, the majority of the visual field does not provide detailed description of an object. This larger portion is the peripheral component and is used in establishing a sense of relative spatial order of the object. It is this combination of these two components that enables the reader to both focus on the lines of text (foveal) and immediately shift from the end of one line to the beginning

to the next line (peripheral). Experiments by Watanabe have shown that if only a foveal component is permitted, the visual search becomes slower and more sequential than when both components are present

The ability to inspect fine detail without a sense of the larger total object contradicts the Gestalt theory that objects are identified by their complete state vice any analysis of their features. More recently, the Gestalt approach has been theorized to hold only for more simple objects, and those that are well known to the observer. The support for a more sequential search has been shown in experiments where the complexity of the viewed object is varied. Subjects have been measured to require a longer time to identify more complicated objects, which follows from the need to check more individual components. It has also been shown that a subject takes longer to recognize a previously specified object than to reject a non-prescribed object. In a sequential search of a prescribed object, each component must be compared with the corresponding part of the specified object, whereas the presence of only a few non-matching features enables the observer to reject the object as being different. Both these results conflict with the Gestalt theory.

The supposition that visual perception and recognition are composed of fairly ordered and identifiable fixed paths - called "scan paths" (Noton and Stark, 1971) was developed by experiments that in general show that observers do not follow a random viewing path. Figure 3 shows the recorded fixations of an observer looking at the drawing of a polygon and the sequence of the fixations in an eight second time frame. The scan path is clearly discernable in fixations 4 through 11 and 11 through 18. While scanpaths were not always observed, the tendency was for the observer to exhibit a scanpath.

B. HAPTIC RECOGNITION

The ability to detect one's surroundings through bodily contact is known as the haptic system. Haptic, from the Greek "able to lay hold of", is defined as "the perceptual system by which animals and men are literally in touch with the environment" (Gibson, 1966, p.97). The haptic system encompasses the entire body - muscles, joints, skin - and provides information on the interaction between a body and its environment. In humans, the two primary parts of the haptic system are the tactile receptors and the physical structure of the body. The haptic system, unlike other perceptual systems such as the auditory or taste-smell, is both a passive and active system. The passive mode detects motion, contact, proximity, and in general the source of the stimulation. Active

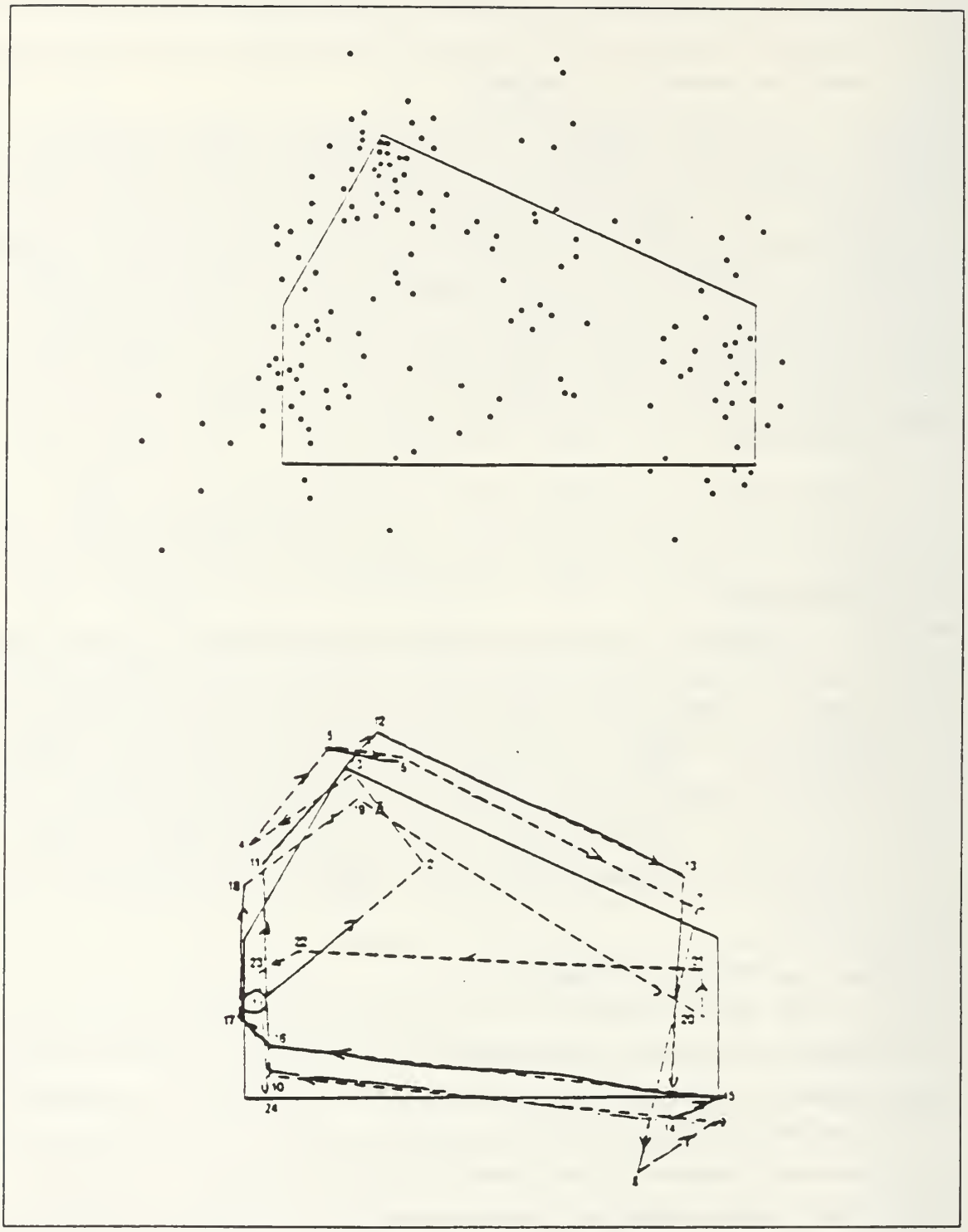


Figure 3. Foveal Positions and Order of Saccades(Noton and Stark,1971,p.36)

perception, or exploratory search, detects tangible physical properties such as object size, shape, surface texture, and hardness.

Proprioception, or kinesthesis, the awareness of sensation, has several forms. Muscular proprioception is the body's ability to judge muscle tension and force. Articular proprioception detects the body's position through joint angles. Vestibular proprioception includes receptors in the inner ear which provide for balance and equilibrium. Cutaneous proprioception is the "touch" or tactile sensation whereby subcutaneous mechanoreceptors are stimulated by contact with or proximity to an object.

The haptic sensation cannot provide the detailed analysis of the foveal vision component, however its ability to provide information to the recognition process should not be considered unimportant or subordinate to vision. Indeed, the haptic ability of the sightless to provide comparable perception is an indicator of its power. "Haptics is not so inferior to optics ... since the blind depend upon it for a whole realm of useful perception." (Revesz, 1950)

C. COMPARISON OF SEARCH MODES

The localized information provided by haptic sensing can be considered analogous to the narrow scope of the foveal field. Research with a force-reflecting telemanipulator, which provides a kinesthetic sense, has shown the highly sequential search strategy characteristic of foveal-only search. (Acosta, 1991) The analogy between haptic and visual search and the possibility for modeling full vision through a combined haptic vision system is the aim of this research.

1. Search Descriptors

Several different qualitative and quantitative measurements have been developed to analyze a subject's search strategy once specific fixation points have been located. One of these is the code circle, which characterizes the manner of the search. Figure 4 shows an example of a search path and code circle for the letter "A". The first drawing shows the lower case letters which represent the individual features of the object. The second drawing is the search path of the letter. The arrow pointing inwards at the lower left corner of the "A" represents where the initial contact was made. The dashed line indicates where the subject broke contact with the object after fixating on the right side ("f") and then regained contact on the lower right horizontal leg ("h"). The outward arrow denotes the last fixation prior to completion of the search. Features which are searched sequentially are indicated by connecting lines on the outside of the

code circle. A search with scanpath tendencies is represented by lines across the interior of the code circle. An interrupted search is shown by a connecting line on the outside of the circle that does not connect two adjacent features. The third picture shows the code circle, with lower case letters located around the perimeter corresponding to the individual object features. The smaller circle contains the features for the internal triangular pocket. The progression of the arrows on the code circle reflects the sequence of fixations. (Acosta, 1991, pp.52-54)

Another method of examining search strategies is to assign a character string to the sequence of fixations. In the previous example, the sequence of fixations is represented by the string [**aqknbdebfh**]. By comparing this string to a previously defined one, the similarity of the two sequences can be quantified through means of string editing, which examines the "cost" of transforming the observed into the predefined string.

> Editing a string has three basic operations - substitution, deletion, and insertion. A "cost" for each such operation must be defined. For example, substitutions are assigned a cost of "2", deletions and additions a cost of "1". To then transform a string observed as [**A C A**] the previously defined string [**C A D A C**] requires inserting a "C" at the beginning and at the end (cost "1" each), and substituting a "D" for the middle "C" (cost "2").

By defining the value of the sum of operations as the "distance" between two figures, a comparison of the distances obtained from various observations can establish the "similarity of the sequence of visual fixations". (Hacisalihzde, Stark, Allen, 1990, p.7)

A method of determining the progression of the search from one observed feature to the next is the sequence ratio, Sr. This is defined as the number of sequential fixations divided by the quantity of the total number of fixations minus one. Therefore, since the sequence ratio lies between zero and one, it may be expressed as a percentage. For example, using the object in Figure 4, the sequence [**defghjklklmopopqrstu**] has 18 sequential features, therefore a sequence ratio of 90%. This was used in comparing the full vision search, which with its saccadic tendencies has a low Sr ($\approx$10%), to a haptic-only (or foveal-only) search, where the search is highly ordered and sequential, and has a high Sr ($\approx$95%).

2. Foveal Visual Search

Work performed by Watanabe examined the observations of subjects when their vision had been modified. Using equipment that showed the location of where a subject was looking, and then masking either the foveal or peripheral component, Watanabe was able to determine changes in the search strategy. When full vision was allowed, the

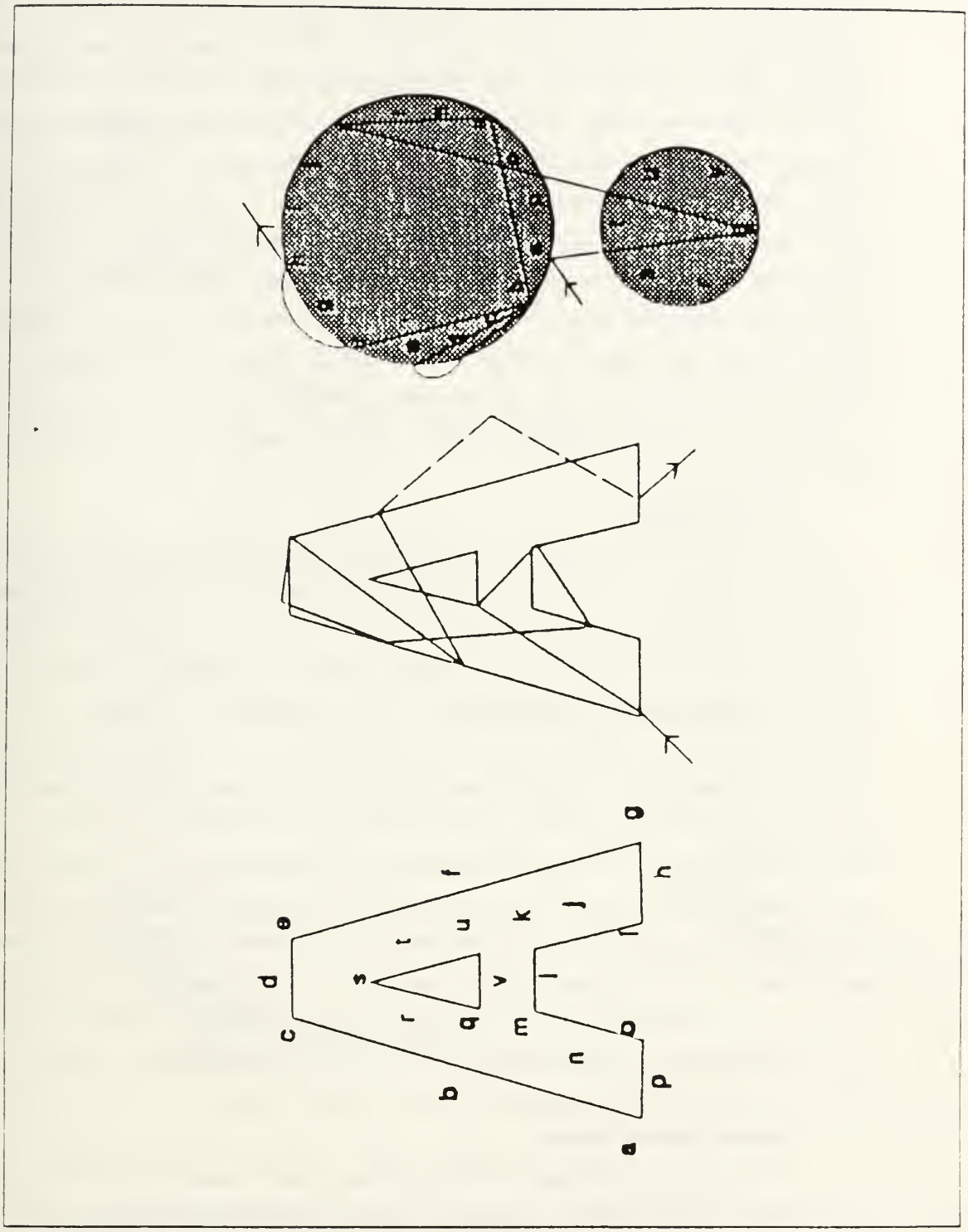


Figure 4. Search Path and Code Circle (Acosta, 1991, p.53)

visual fixations closely resembled the saccadic tendencies of the scanpath theory of Noton and Stark. In the experiments where the foveal component was masked, the fixations oscillate to the left and right of the target in order to try and obtain the detailed information which is absent when looking directly at the object. Video recordings of Watanabe's work show that when the peripheral component was masked, the subject's fixations slowed and became more sequential in nature. A subject seen reading from a book is unable to proceed directly from the end of one line of text to the beginning of the next line. The recorded visual search slowly looked for a continuous path in the direction of the left-hand side of the page, and then vertically towards the proper line. there was no evidence of any scanpath characteristics present. This foveal-only search exhibited similar patterns as the haptic-only explorations studied by Acosta, thus supporting the hypothesis that a haptic input could be an adequate substitute for the foveal vision component.

3. Haptic Search

Similar to the concept of two supporting subsystems for visual search, the haptic, or touch system can also be thought of as having two separate channels, the tactile system, and the kinesthetic system, which obtains information through the spatial orientation of body parts. In order to study the effect of each haptic sensory system, Driels and Spain developed experimental work that decoupled the tactile mode from the kinesthetic mode by having subjects use a telemanipulator (conceptualized in Figure 5) to identify remote objects. The telemanipulator provided force feedback through system of antagonistic cables and pulleys which reproduced the operator's movements. Qualitative observations of the tests conducted led to the supposition that object identification is initially based upon an accumulation of knowledge about individual features. This non-Gestalt approach was further developed in subsequent work by Acosta who showed that such a decoupled haptic system caused the subject to search in much the same highly sequential fashion as the foveal-only vision search. The lack of a "global" recognition capability to see the object in its entirety thus becomes comparable to the lack of a peripheral vision component in visual object search.

4. Hybrid Sensory System

The similarity between the foveal visual search done by Watanabe and the haptic search work done by Acosta indicates that substitution of a haptic sensory input for the foveal vision component can be used in a model for a full vision system. A degraded visual cue, representing the peripheral component, will provide the gross spatial information; a haptic input will provide the detailed narrow information required for

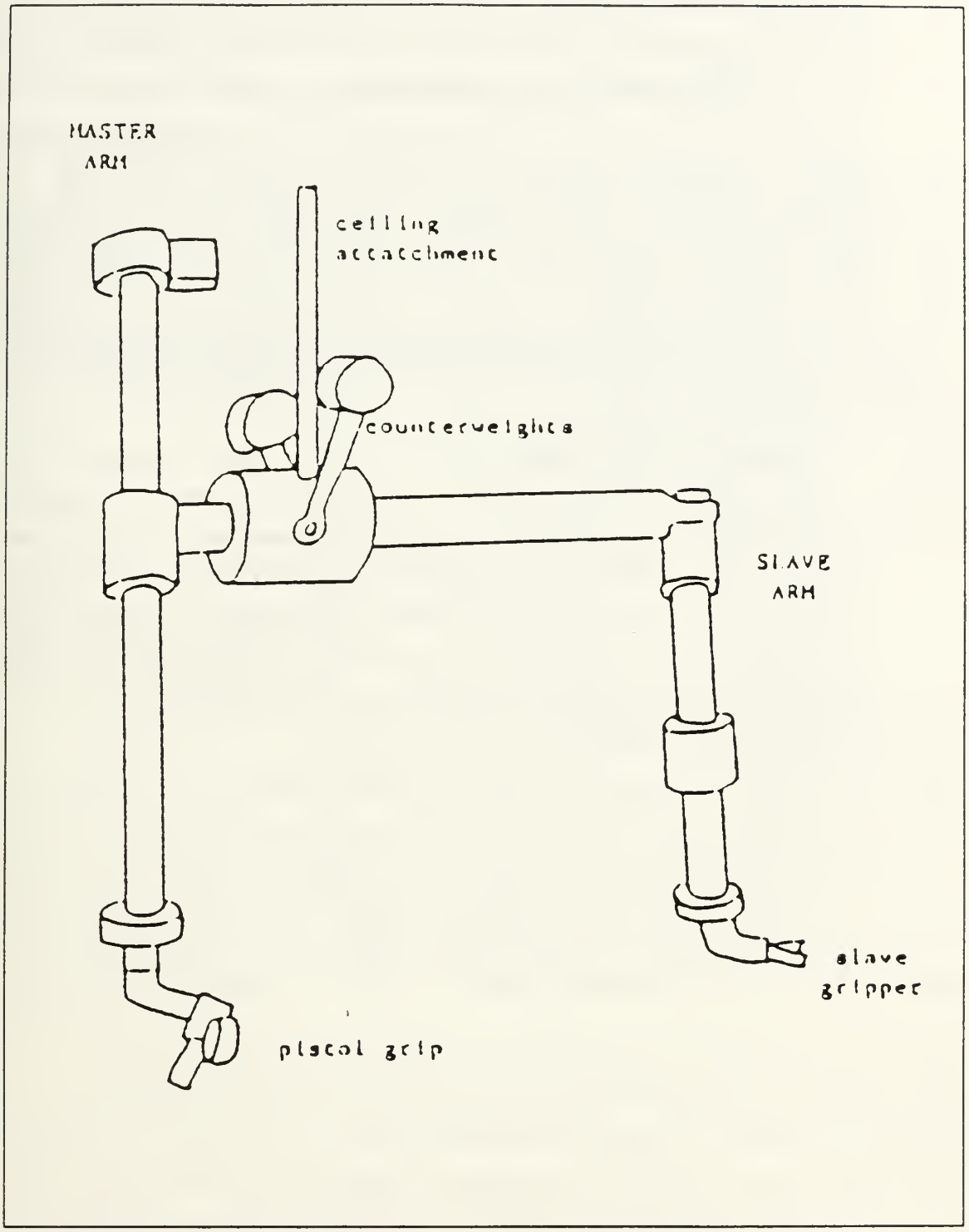


Figure 5. Conceptualization of Telemanipulator

individual feature recognition. A method of combining these two modes into a hybrid full vision system can be tested, and if successful, provide a means for improving the sensory acquisition of an ROV at a reduced cost. An equivalent full vision system would not require the same quality visual sensors necessary for foveal vision in a direct viewing system. Lesser-grade optical sensors combined with a haptic sensory input would result in lower cost while providing the same sensory capabilities as a full vision system. Indeed, in many environmental conditions, even the most well-designed optics may not yield sufficient resolution to allow remote foveal recognition. A remote haptic channel is not subjected to the same visual limitations as the normal foveal component, hence it provided a more efficient, possibly less expensive means to accomplish detailed object recognition.

D. OBJECTIVES OF THESIS

The objective of this research is to examine the search strategy of a hybrid haptic visual system to determine future sensor requirements for the next generation remotely operated vehicles. The substitution of haptic feedback for the foveal vision component is analyzed to determine whether such a system is an adequate model for full visual search. This system would provide a much less costly alternative to a higher grade optical sensor system and would prove more useful in environments where vision is restricted by water conditions.

III. EXPERIMENTAL DEVELOPMENT

A. OVERVIEW

Based upon the previous data of haptic search approximating the foveal vision component, a model for full vision was developed using a computer based vision system to simulate the peripheral vision component. Test subjects were shown a digitized video image of the object to be identified. In order to simulate the unfocused nature of the peripheral component, a computer generated program was employed to digitize the object into a "mosaic" or tile pattern. This allowed the subject to sense the general size and shape of the object, but did not give sufficient detail to allow for recognition. A force-reflecting telemanipulator utilizing haptic recognition to provide detailed feature information was considered as an alternative for the foveal vision component. The combined nature of these two sensory inputs as an acceptable model for full vision search was analyzed by means of quantitative measures of recognition.

B. SYSTEM COMPONENTS

1. Telemanipulator

A seven DOF, CRL force-reflecting telemanipulator of the terminus type was used in this research. A cable pulley system allowed the operator to sense the forces experienced at the end effector through a pistol grip handle. A parallel gripper locked a plastic brace-mounted steel probe. A high current LED was mounted in the end of the one-quarter inch diameter probe. The LED provided visual feedback to the observer via projection camera monitor during the combined search mode. Figure 6 shows a schematic of the equipment set-up. The LED also served to reduce the friction between the probe and the taskboard. Figure 7 shows the telemanipulator and taskboard arrangement.

Haptic probing is accomplished by decoupling the tactile sensory system from the proprioceptive system by placing the telemanipulator between the operator and the taskboard. This serves as a sensory filter and experiments by Driels and Spain have shown that when compared to direct manipulation of an object, the effect of haptic-only probing is a degradation of the subject's proficiency in identifying an object.

Several mechanical effects of the telemanipulator contribute to the subject's reduced ability to recognize objects. Friction between the probe and the taskboard causes "mechanical noise" which makes object recognition more difficult. If the subject pushes

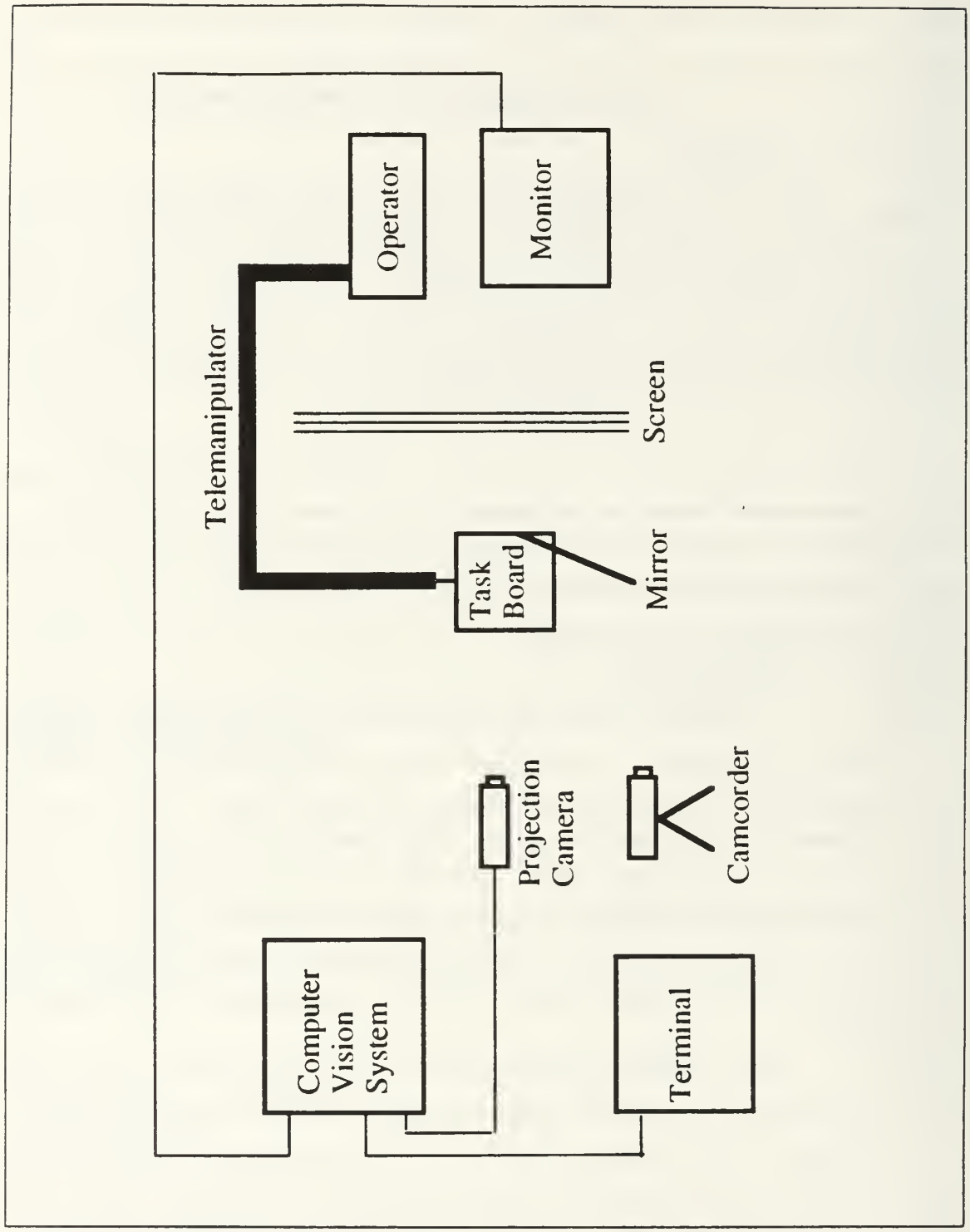


Figure 6. **Schematic of Equipment Arrangement**

Figure 7. Telemanipulator and Task Board Arrangement

the probe tip with too great a force in the direction normal to the plane of the taskboard, the ability to distinguish the contact force with the edge of an object and the normal friction force is lost. Familiarity with the necessary force required to just maintain contact on the surface of the taskboard is an essential element of subject training. The size of the individual features of the object must be sufficiently large enough that the end effector can examine it in detail. The effect which is most dependent upon operator skill with the manipulator is inertia. The mass of the manipulator arm makes it very slow to respond; until proper skill level is developed, the ability to detect abrupt changes in feature orientation, such as in exterior-angled corners, is limited. The tendency to "overshoot" an exterior corner of an object is quite common during the training phase, and even well trained operators suffer from an occasional loss of proper probing speed control and consequently miss the corner of an object.

2. Vision System

To simulate the peripheral vision component, a method to degrade the image quality had to be developed. A computer program using the intrinsic commands of the Intelledex ® Intellevue ™ 200 Vision System was used. This system utilized a variation of the Microsoft © BASIC language called Vision BASIC ™. The specific commands issued included:

-VSNAP: An image acquisition command that writes the real-time digitized image currently seen through the camera to the display RAM.

-VDIG: An image processing command issued after VSNAP that displays the contents of the display RAM. Once this command is issued, no changes in the camera's viewing field affect the displayed image.

-VPPEEK: An image processing and display command that samples the gray-scale value of the specified pixel.

-VPPOKE: An image processing and display command that returns a specified gray-scale value to the indicated pixel in the display RAM.

The complete program, listed in Appendix A, sampled each of the pixels in a predetermined block size (31x30 in this research), averaged the sum of the gray-scale values of all 930 pixels in the block, then returned that average value to each pixel in the block.

Once the program had completed running, a general purpose system function command, VBOTH, was issued. This command displayed the digitized image currently in the display RAM superimposed upon the actual image. This allowed the movement of the probe to be seen on the monitor at the same time as the digitized image. So as

not to have the image of the actual letter appear on the monitor, the f-stop on the projection camera was set to the smallest opening. The brightness of the LED in the probe tip was then the only "live" image which appeared on the monitor. To further ensure that no other part of the "live" image came through, a large black cloth screen with a dull surface was mounted on the wall behind the manipulator, reducing the amount of light reflected off the white wall.

3. Video Monitoring

In order to analyze a subject's search strategy, a video recording of each run was made. A video recorder was mounted behind the taskboard and recorded the movement of the probe tip as each subject tried to identify the specified object. Because the probe tip was not visible from in front of the task board, the camera had to be positioned behind the task board. To have the recording appear in the correct orientation, and not in the reverse image, an 18 inch square mirror was mounted to the wooden frame of the task board. Figure 8 shows the position of the camera shooting an image of the letter "B" from the reflection in the mirror. This arrangement allowed both the video recorder and the projection camera to be out of the way of the telemanipulator and permitted the operation of the video recorder away from the field of view of the subject in the combined search mode. An external microphone was used to capture the verbal comments of the subjects to provide additional clarification of the search strategy.

A significant amount of time was required to initially develop the arrangement of all equipment in order to achieve proper lighting for both the projection camera and the video recorder. The background light available during daytime provided a much different source than the overhead fluorescent lighting used at night. Adjustments to the task board, mirror, and camera positions were required prior to each session to obtain the highest resolution picture.

C. SUBJECT TRAINING

A dedicated training phase was required of all subjects in order to develop familiarization with the operation of the telemanipulator, whose large mass and length yielded a significant amount of inertia to overcome, certainly more so than a human arm. The ability to make slight adjustments and understand the time lag response of the manipulator required considerable practice.

Initial training was conducted by having the subject look at the end effector while probing an object. After that initial exposure to the force feedback generated by contact with the object edge and the task board, the subject was shielded from the task board

Figure 8. Projection Camera Arrangement

by a large curtain. Further practice helped the subject develop confidence in identifying the letters, which were placed normal, upright position. After observing the subject exhibit a level of skill that enabled them to identify the object with a 90% confidence level, the letter was rotated to randomly selected orientations. Once a similar level of proficiency was shown, actual data collection commenced.

The integration of the visual search component was accomplished by first showing the subject what a processed image looked like, and then conducting several practice runs. To reduce the any possible biases, the subjects were never told that any of their efforts were not being video taped. Standardization between all runs was emphasized to ensure no subconscious changes in the subject's search habits.

D. EXPERIMENT PROCEDURES

Three operators were trained as subjects for this research. Each subject was given a similar series of objects to identify. The objects chosen were nine inch long block capital letters that were randomly oriented on the taskboard to avoid having the subject "guess" the object based upon initial probing had the letter been in an a normal upright position. Letters of the alphabet were chosen so as to provide a common object set for all subjects. Utilizing a set of objects that do not have the same recognizability to all observers adds a possible bias to the subjects' search pattern and which would be undetectable in any of the measures of recognition. To ensure standardization and to avoid any pre-planned search strategies, no specifics as to the manner of identification or to any time constraints were given. The only instructions provided to the subjects were to have a high degree of confidence in stating what they thought the letter was. Verbal comments were encouraged throughout the search process to assist in analyzing the data.

An object set of eleven different letters was used in the data collection. The letters are listed in Appendix B. The lower case letters around the perimeter of each letter corresponds to a particular feature, such as a long straight edge, short straight edge, long curved surface, short curved surface, acute angle, obtuse angle, corner, etc. These are combined in a string to qualify the search strategy and quantify several measures of recognition (e.g., sequential ratio, reversal rate, recognition rate) that are discussed in Section IV.C.1. The object set was the same as that in the research done by Acosta in order to corroborate the results of the haptic-only search. The same set was also used for the combined search mode to more closely examine the differences between the two modes. To prevent the subjects from recognizing that the object set was only a subset

of the entire range of possible objects, test runs were also conducted using other letters. The subjects were not told of this and all other facets of the data collection process were identical so that the subject was unaware that he was being given a "placebo" which would not be used in the data analysis. This also served the purpose of exposing the subject to more individual features thereby expanding the number of possible choices each would have to make in confirming the object.

In the haptic search mode, operators were visually and audially masked to preclude receiving any cues from either watching their hand movements or listening to noise coming from contact between the probe and the object. In the combined haptic visual search, the computer vision system was used to acquire and process the object into a digitized "mosaic" image. By varying the pixel block size of the program listed in Appendix B, differing levels of image grain were obtained. Figure 9 shows the letter "M" prior to being digitized. Figures 10 through 14 show the letter "M" which have been processed into various pixel block sizes ranging from 16x17 (Figure 10) to 35x30 pixel block size (Figure 14). The images produced by the finer block sizes (16x17, 21x20, 25x20) did not provide sufficient image degradation, while the images processed into the 31x30 and 35x30 pixel block sizes were both adequately degraded. The nearly square 31x30 block pattern was considered more desirable than the rectangular 35x30 block pattern and was selected for use in this experiment. This image provided the subject with a general spatial sense of the object, but not enough fine detail allow for immediate recognition. An LED was fitted into the end of the probe; its location on the monitor gave the subject a reference point on the digitized image.

The actual digitization program took approximately six minutes to complete its progression across the monitor screen. During that time, one or two haptic-only runs were conducted. This provided a more balanced sequence of tests and also kept the subjects more engaged in the experiment by not having so much "dead time" (relative to the actual time spent on each individual run).

After establishing proficiency using the telemanipulator, actual data collection was done with each subject in one to one and one-half hour time blocks over a period of several weeks. Both physical and mental capacity to perform dextrous tasks rapidly deteriorates after longer sessions. By collecting data for a shorter period of time on an every other day basis, subjects maintained both their manipulator skill and interest in the experiment, and the time off between sessions prevented the subjects from "memorizing" feature sequences of particular letters.

Figure 9. Letter "M" Prior to Digitization

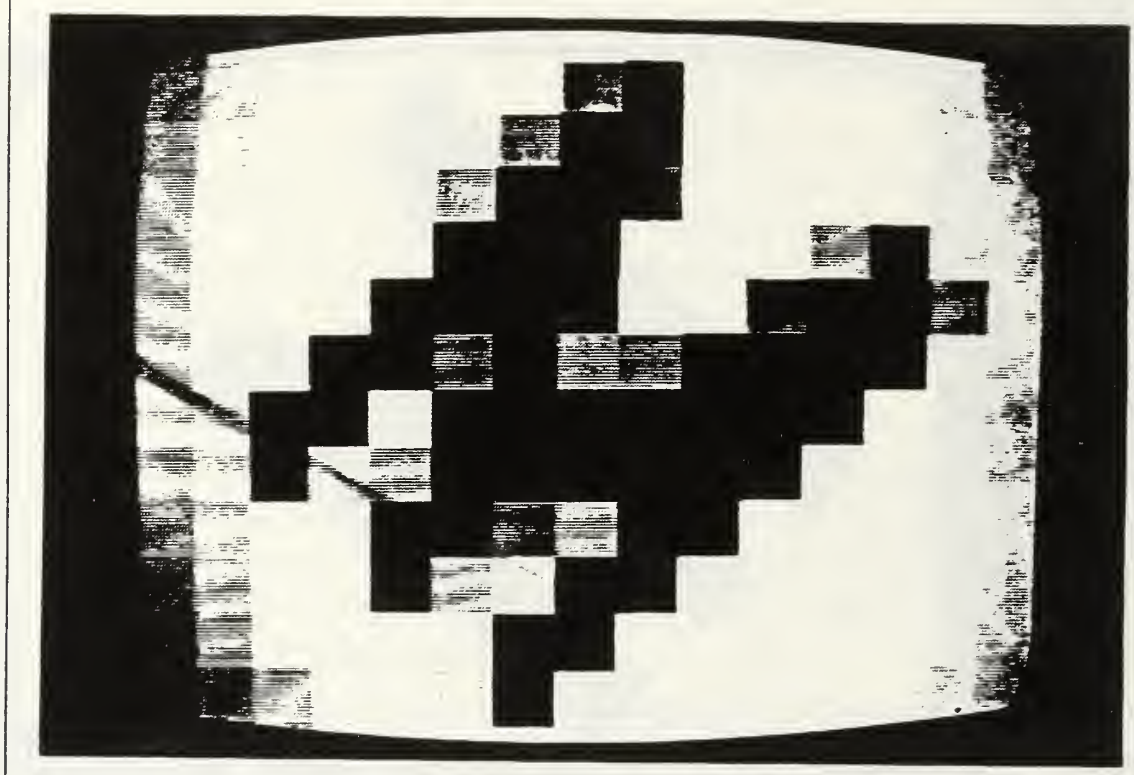


Figure 10. Letter "M" Digitized into 16x17 Pixel Block Size

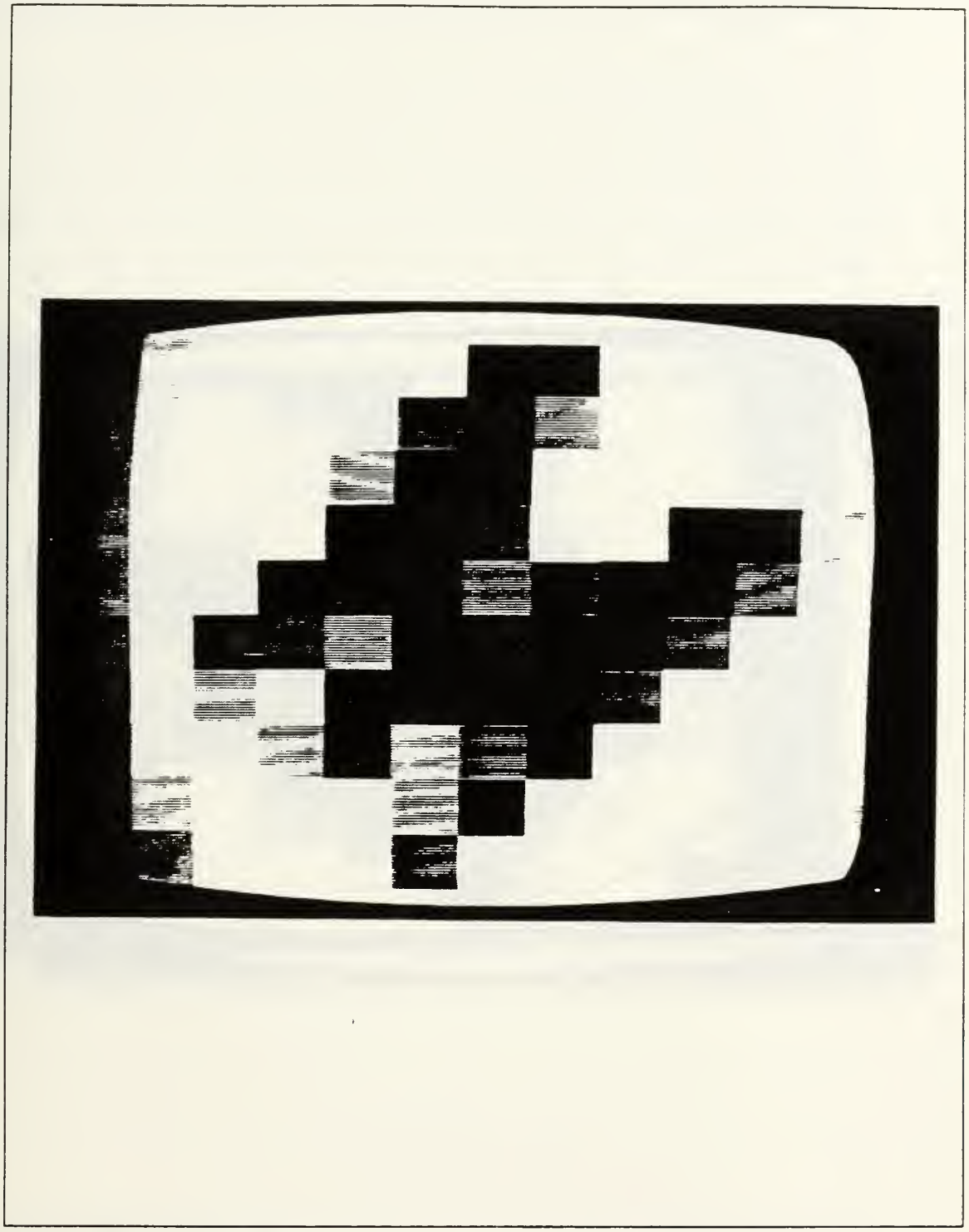


Figure 11. Letter "M" Digitized into 21x20 Pixel Block Size

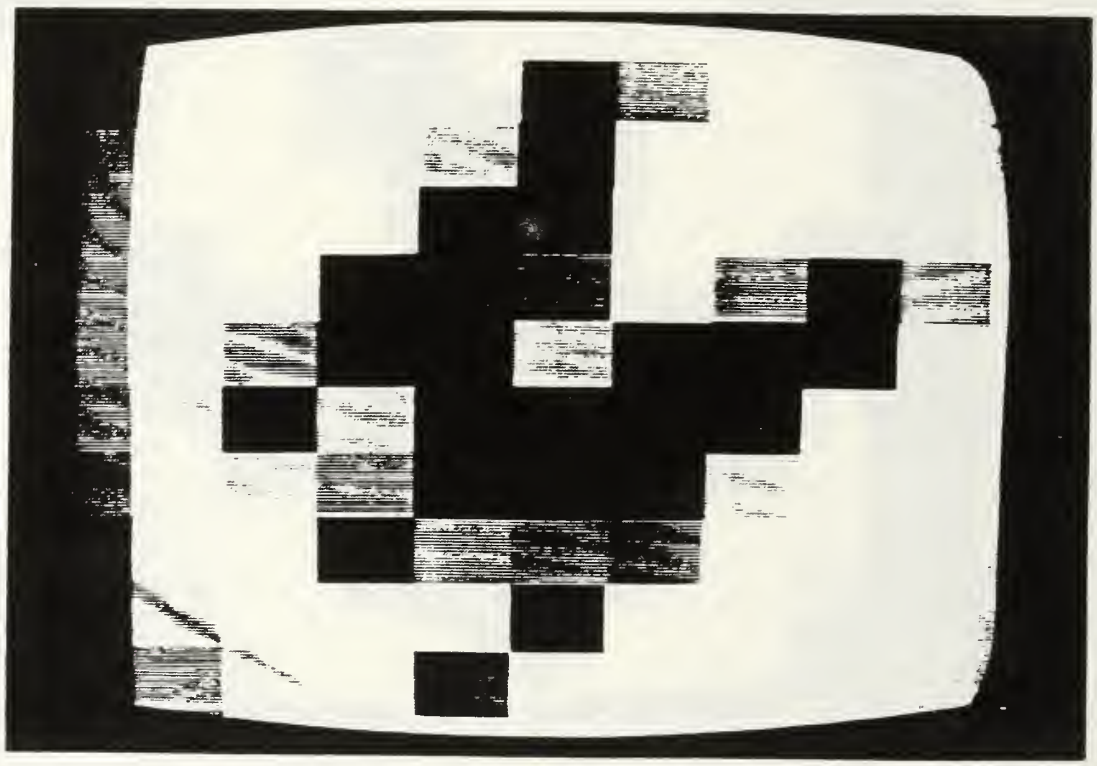


Figure 12. Letter "M" Digitized into 25x20 Pixel Block Size

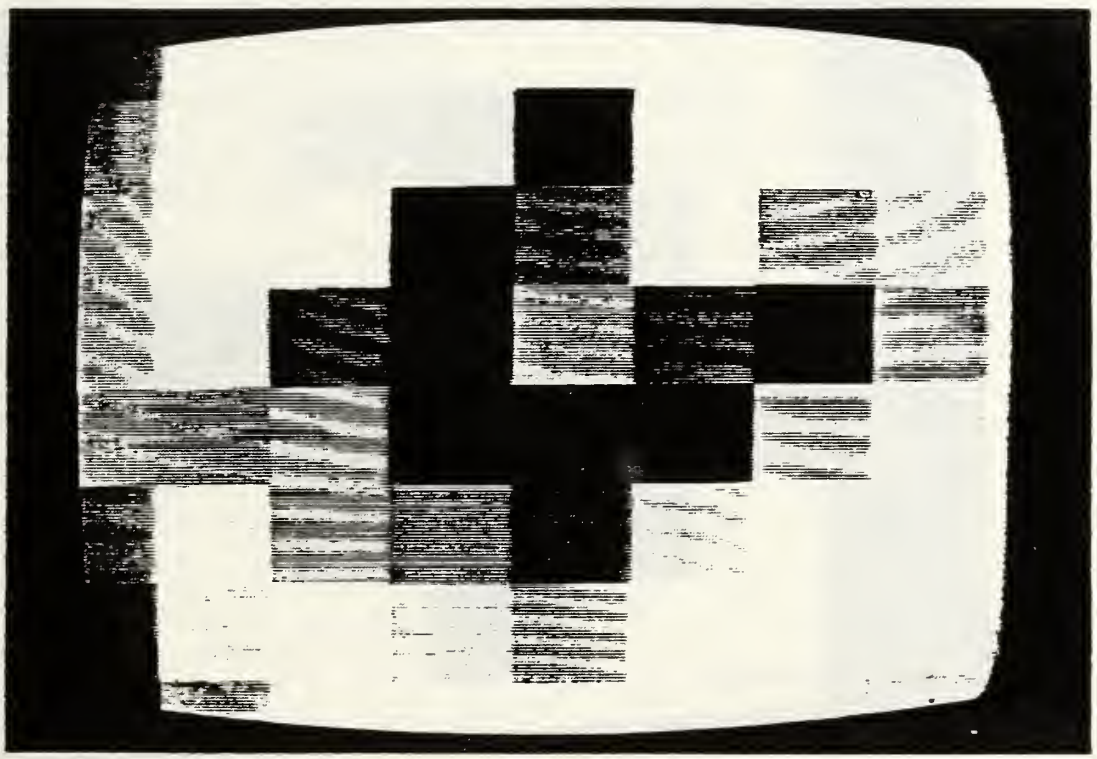


Figure 13. Letter "M" Digitized into 31x30 Pixel Block Size

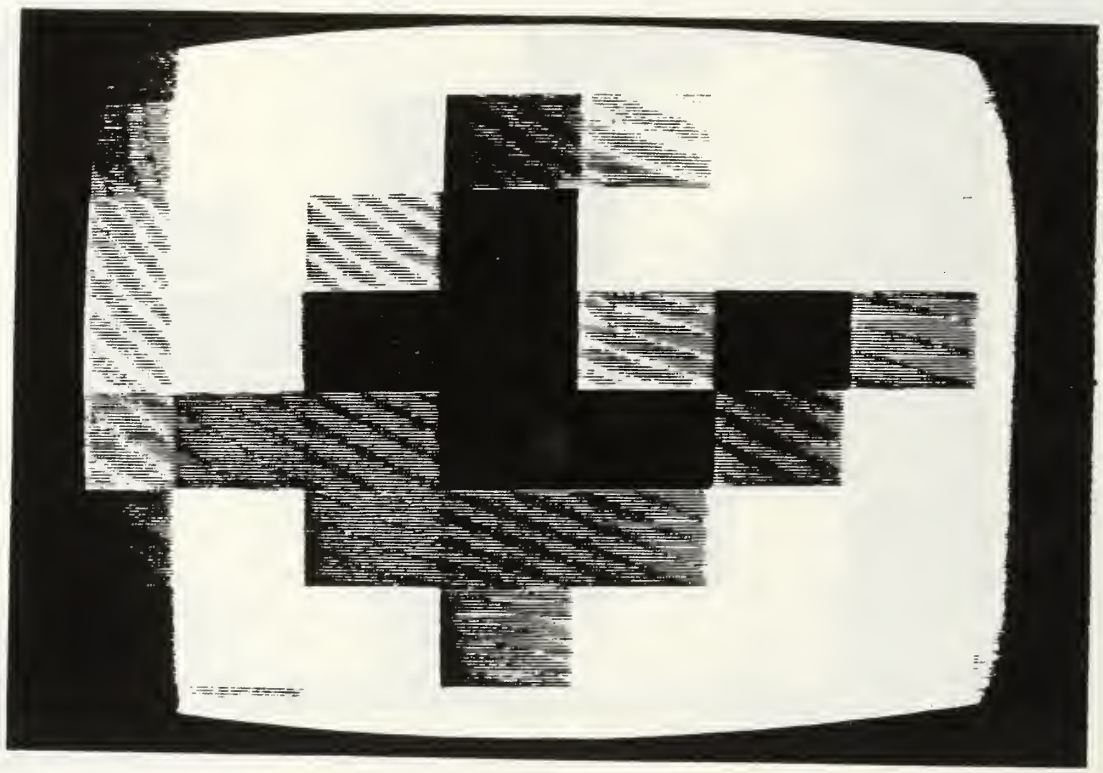
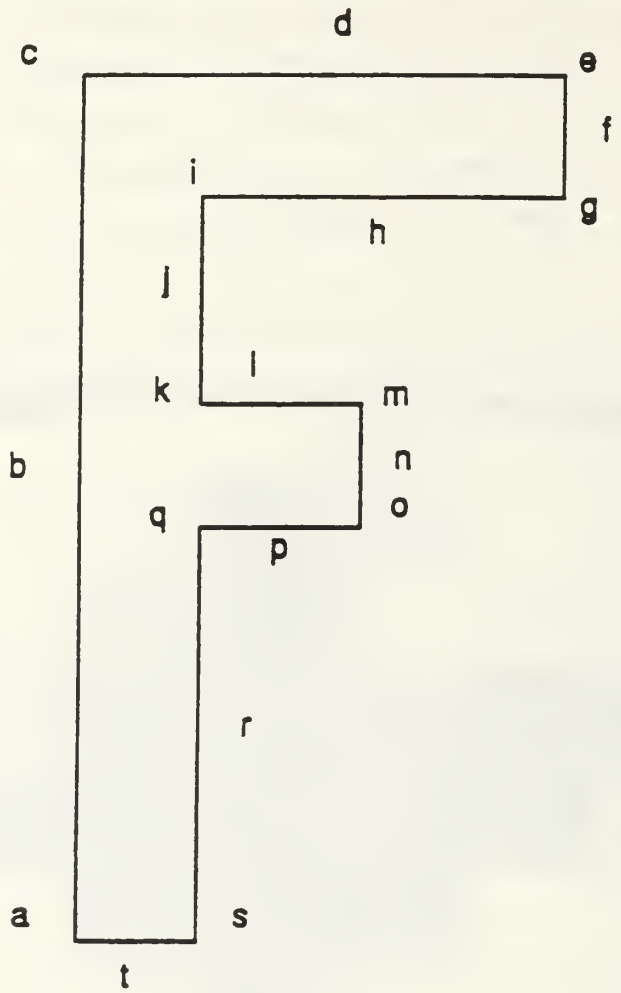


Figure 14. Letter "M" Digitized into 35x30 Pixel Block Size

E. DATA COLLECTION AND PROCESSING

Detailed analysis of the search strategy during each run required the ability to identify every individual feature probed. To accomplish this, a video recording of each subject's test series was made, along with a recording of their verbal comments. After all subjects had completed their runs, the video tape was viewed in order to identify the search mode. Figure 15 is an example; the string listed corresponds to the search path of the letter "F" by Subject #3 for both the haptic-only and combined haptic visual search. Similar strings for all runs of each subject were made. The results are compiled in Appendix C, which lists the raw data for each subject broken down by letter and by quantitative measure of recognition.

Extreme care had to be taken in analyzing the videotapes. The frequent rapid "back and forth" motion of the probe made it difficult to determine whether or not a particular feature had been identified. Also, the operator's ability to maintain contact with the edge of the letter as the probing progressed along an external corner was not always observed on the tape in real-time speed. Either a slow motion or frame-by-frame replay was necessary to determine whether the subject had in fact known he had identified a corner. Verbal comments were useful in clarifying this, but more often than not, a sequential frame review of the data was required.



HAPTIC

[bcdcbcdfedeghijkjijklkjijklmljklm
nopqpqrsrqrqpqpolklmnopqpojkjihg]

COMBINED

[bcbabcdedefhihghihghgfhgehijkjijkjijkjihijklmnk]

Figure 15. Search Strings for Letter "F"

IV. RESULTS AND DISCUSSION

A. MEASURES OF RECOGNITION

Six specific categories of recognition were used for comparison between the search modes. These are the sequence ratio, the total number of features probed, time to recognition, number of reversals, recognition rate, and reversal rate. Two of these, the sequence ratio and the total number of features probed, were also used to compare the results obtained in the haptic-only search with that done by Acosta.

The sequence ratio, Sr, defined as the total number of sequential probings divided by the total number of features probed minus one, was used by Acosta to compare the highly ordered haptic search to the random full visual search. The total number of features probed, time to recognition, and the number reversals - reversals defined as the number of changes in direction during a run - were considered "raw" data; these three quantities are very dependent upon the object to be identified and the operator's technique. To get a better comparison of an individual subject's overall search strategy, two "normalized" rate-based results were calculated. The recognition rate is defined as the total number of features probed divided by the time to recognition. This provides a quantitative measure of the "quickness" of a subject's probing. The reversal rate, defined as the number of reversals divided by the total number of features probed, is a numerical expression for the "back and forth" probing technique frequently exhibited by all subjects. These two rates are interdependent and must be considered together. A high recognition rate does not necessarily mean that a subject is rapidly exploring the entire object; if the reversal rate is also high for that same letter, it is an indication of a fixation over a particular group of features of that letter (such as the "v-shape" at the top of the letter "M"). Multiple explorations over a restricted area indicates that the subject does not have a good feel for the "big picture" and is using an established reference point to build up confidence prior to continuing his exploration. On the other hand, a low recognition rate does not mean that the subject is having difficulty identifying the object. He may have an estimate of the next feature to be searched and is taking his time to confirm that supposition. However, if the reversal rate is high, the deliberate, thoughtful search pattern may mean that the subject does not have a good idea of the letter, and is repeating his search over a small area in hopes of finding a unique feature (such as the cusp of the "B", or the tail of the "Q") which may lead to immediate recognition.

B. HAPTIC COMPARISON

Table 1 summarizes the data obtained from the haptic-only search. The average sequence ratio all three subjects, 93.3%, is comparable to the value of 95% obtained by Acosta. The average of all three subjects' total number of features probed is 80.9, also comparable to the Acosta result of 87.0 features. These similar results confirm that a haptic-only search is an adequate substitute for the foveal vision component in a hybrid sensory system.

Table 1. RESULTS FOR HAPTIC-ONLY SEARCH

	SUBJECT #1	SUBJECT #2	SUBJECT #3
Sequence Ratio (%)	93.59	96.39	89.82
Ave # of Features	122.0	52.17	68.43
Ave Recognition Time (seconds)	121.6	86.00	68.57
Ave Recognition Rate (features second)	1.000	0.609	1.056
Ave # of Reversals	22.00	9.50	22.57
Ave Reversal Rate (reversals second)	0.175	0.193	0.353

C. COMBINED VISUAL/HAPTIC SEARCH

1. Data Analysis

Table 2 lists the results of the combined search for each of the subjects. These numbers are averaged from the compilation of data contained in Appendix C, which lists the results for each subject search of each object broken down into all six calculated categories.

a. Total Number of Features Probed

The average number of features probed per object was noticeably greater in all three subjects for the haptic search than for the combined search. The increase ranged from 18% to 40% and averaged almost 29%. The average in the haptic-only search was within 10% of Acosta's results. The range of the number of features probed in each subject's search varied widely for different letters, reflecting the innate differences between operator skills and probing techniques. Further, while every effort was made to ensure standardization of test procedures, the changing nature of physiological and

Table 2. RESULTS FOR COMBINED HAPTIC/VISUAL SEARCH

	SUBJECT #1	SUBJECT #2	SUBJECT #3
Sequence Ratio (%)	93.77	98.20	92.24
Ave # of Features	87.09	42.86	41.40
Ave Recognition Time (seconds)	122.5	88.86	49.70
Ave Recognition Rate (features second)	0.762	0.507	0.828
Ave # of Reversals	14.00	5.29	15.30
Ave Reversal Rate (reversals second)	0.164	0.123	0.347

psychological influences from day to day (i.e., from session to session) may have affected the subject's performance. Therefore, no direct correlation of the raw number results of this category is considered appropriate. The standardized rate-based results of recognition rate are more accurate measures of the true nature of each subject's efforts.

b. Time to Recognition

The time to recognition is considered the most subjective measure of a subject's search strategy. The nature of the peripheral component as modeled by the computer digitization process makes it possible that the altered image could be more "clear" to one observer than another. This characteristic may manifest itself in a subject's search technique. If one subject has a better intuitive feel for what the digitized image is than does another subject, his search should be more concise and he is likely to mentally process a greater amount of information in the same time frame. This trait could also be reflected in a relatively higher recognition rate.

The time to recognition for the first and second subjects was almost the same (within 3%) in both search modes whereas the third subject's average recognition time was over 27% faster in the combined search mode, where the visual peripheral component was available. Since Subject #3 also had a 9% higher recognition rate than Subject #1, and a 63% higher recognition rate than did Subject #2, it can be assessed that Subject #3 had a better ability to distinguish the digitized image prior to commencing haptic search.

c. Recognition Rate

In all three subjects, the recognition rate was considerably higher - ranging from 20% to 31% - for the haptic-only search than for the combined search. This indicated that the addition of the peripheral vision component does not increase the subject's ability to receive and process information at faster speeds. Providing another sensory input actually slowed down the data gathering process. The phenomenon of "sensory overload", where so much information is presented to the viewer that he is unable to make use of any of it, is a potential problem. This habit was sometimes noticeable during the combined search,when the subject would stop probing and concentrate his attention towards the monitor. This increased the time spent in the search and consequently yield a lower recognition rate than if the subject had maintained a continual movement of the telemanipulator. Although the hybrid vision system did not cause complete sensory overload, a real world operator of such a system would have other sensory inputs and distractions. The chance saturating the information processing ability would might exist, and therefore should be considered in the design of the equipment.

d. Number of Reversals

Each subject had from a 50% to 80% increase in the number of reversals in the combined search over the haptic-only search. Much as the time to recognition could not be examined without reference to the recognition rate, the number of reversals, as a "raw" figure, is more useful when considered in the context of reversal rate.

e. Reversal Rate

The reversal rates seen in the haptic mode varied from 7% to 57% higher than in the combined search. The large range of values is attributed to the differences in operator proficiency, and perhaps more importantly, the degree to which a required confidence level is needed prior to stating what the object is thought to be. Though a wide range did exist in the size of the rate increase, the fact that the all three subjects had higher rates in the haptic-only mode shows the quantitative nature of "back and forth" probing, a technique seen in much greater frequency when subjects had no visual cue. This suggests a desire to reconfirm individual features more frequently. Certain features, particularly obtuse exterior angles such as the sides of the "X", were prone to many repetitive probings, in large part (based on verbal comments) on the need to check that there indeed was an angulation, and not just a long straight edge. While the distinction between a straight edge and a near 180° angle would not have shown up in the digitization process, the ability of the subjects to view the LED would have provided a discernable clue.

f. Sequence Ratio

In each of the subjects' probings, the sequence ratio for haptic-only searching was just a fraction below that of their results for combined search. Overall, the average sequence ratio for haptic-only probing , 93.3%, is comparable to that for the hybrid search, 94.7%. Both of these results are quite similar to the 95% result obtained by Acosta. The fact that the values are almost identical in both modes was quite surprising and indicates an overwhelming reliance of the subject on haptically acquired information. This contrasts the premise of this work that the sequence ratio would be closer to the 10% value found in previous work for full vision search rather than almost 95% value in the haptic-only mode. The discovery that the sequence ratio for the combined system does not tend at all in the direction of full visual search is concluded to be the most convincing result that the proposed model does not provide the equivalent of a full vision system.

2. Search Strategies

While an attempt was made to quantify all search techniques, several qualitative observations were noteworthy. The subject's initial exposure with the combined system was much slower than succeeding runs using both inputs. The need to conduct thorough training on the telemanipulator prior to commencing data collection is an unavoidable reinforcement of the haptic reliance. When subjects were first exposed to the hybrid search, there seemed to be a tendency on the operator's part "not to believe their eyes". The subjects were observed performing similar strategy as they had in the haptic-only mode, but they appeared to be concentrating so intently on the visual cue, that they repeated their probings more often than they would after multiple sessions with the combined sensory input.

In an attempt to verify if manipulator practice had prejudiced the subjects towards over-reliance on the haptic input, an observer who had no familiarity with any portion of the experiment was chosen as a "control" check. Using the same equipment set-up and providing the same guidelines as in the rest of the data collection, this subject was given no practice on the manipulator. By allowing this "control" to immediately use the hybrid system, it was hoped to show whether any undue influence would be attributed to either manipulator training or performing the haptic search first. However, no such conclusion could be drawn, as the control subject exhibited a highly sequential search strategy even in the presence of the visual cue. While this sample size is statistically insignificant, the fact that the initial efforts of this "unbiased" search were so

similar to the actual test subjects is further evidence of the inherent reliance on the haptically acquired data.

D. COMPARISONS BETWEEN SEARCH MODES

The most obvious comparison between the haptic and combined search is the almost identical sequential nature in both modes. Based upon previous work, where the sequence ratio for haptic-only search was 95% and for full visual search near 10%, it was believed that the results for a hybrid system would lie somewhere in between. The fact that almost no distinction between the haptic search and combined search results can be made is not totally without precedence, however, as it has been noted that human divers rely extensively on their sense of touch to accomplish their tasks. Since much of their work is done in the absence of visual contact, the need for well-developed dextrous skill is essential.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

-The addition of a peripheral vision component (as modeled by the computer vision) to a haptic input simulating the foveal vision is not equivalent to full visual search.

-In spite of the presence of a visual sensory input, subject reliance on tactile response is the predominant means of deriving localized feature information.

B. RECOMMENDATIONS

-Reliance on haptically acquired data is consistent with human divers experience.

-The haptic sensory channel provides the most reliable source of remote object identification, and future research into the man-machine interface of ROVs should focus on improving haptic search capabilities.

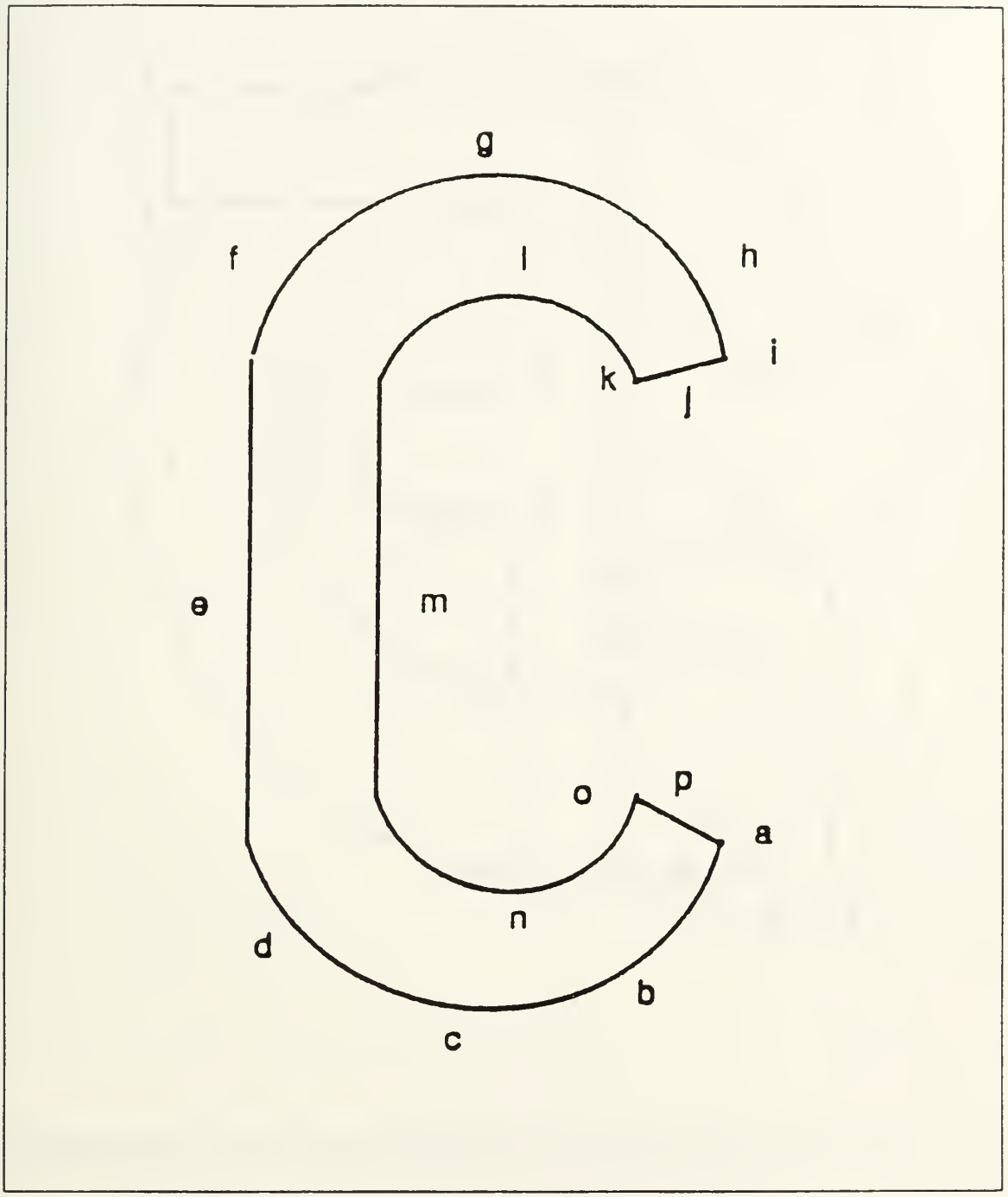
-The substitution of a sonar-type sensor for the peripheral vision component should be tested to develop a better model for a hybrid full vision system.

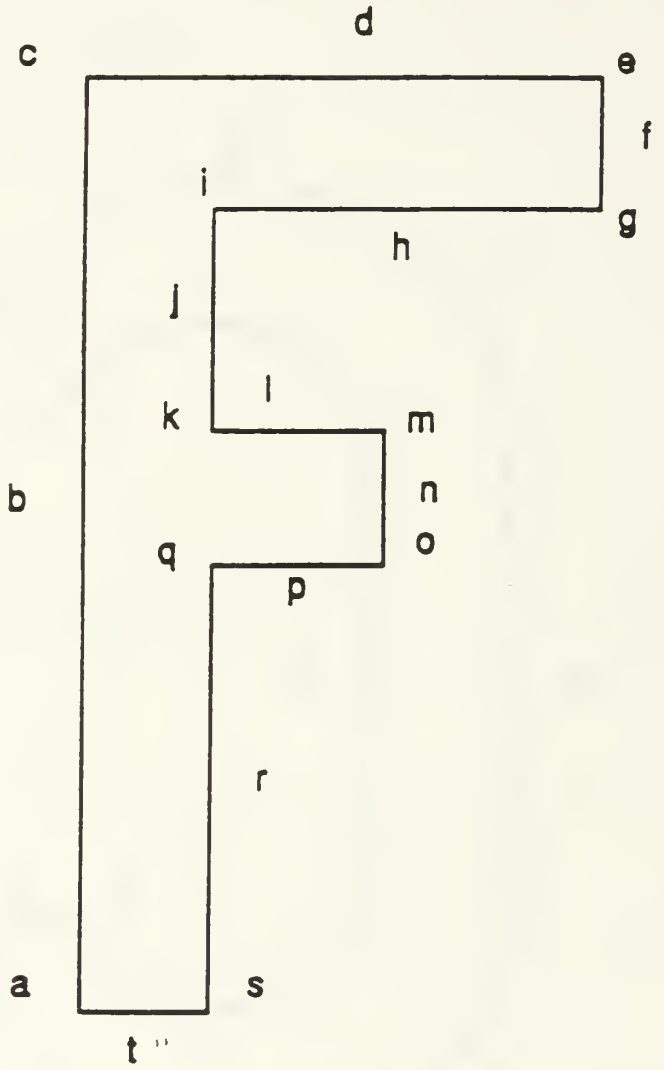
-Future thesis work involving the control of telemanipulators and sensory input should involve live testing with teleoperation devices coordinated through NOSC San Diego.

APPENDIX A. COMPUTER DIGITIZATION PROGRAM

```
10  VSNAP
20  VDIG
30  FOR I = 0 TO 217 STEP 31
40  FOR J = 0 TO 210 STEP 30
50  SUM = 0
60  FOR K = 1 TO 31
70  FOR L = 1 TO 30
80  SUM = SUM + VPPEEK(J+L,I+K)
90  NEXT L
100 NEXT K
110 PIX = SUM/930
120 FOR K = 1 TO 32
130 FOR L = 1 TO 30
140 VPPOKE J+L,I+K,PIX
150 NEXT L
160 NEXT K
170 NEXT J
180 NEXT I
```

APPENDIX B. OBJECT IDENTIFICATION FEATURES

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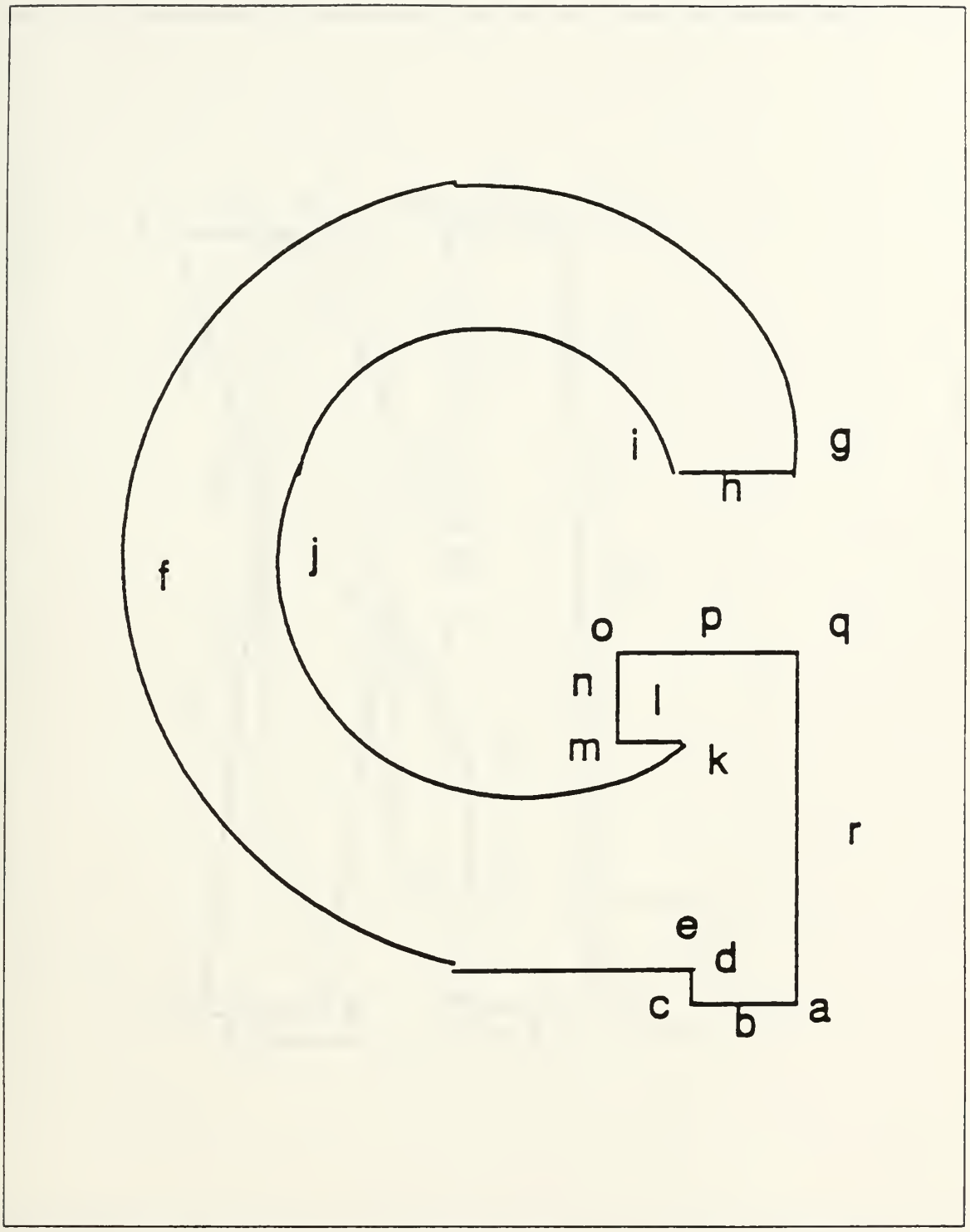
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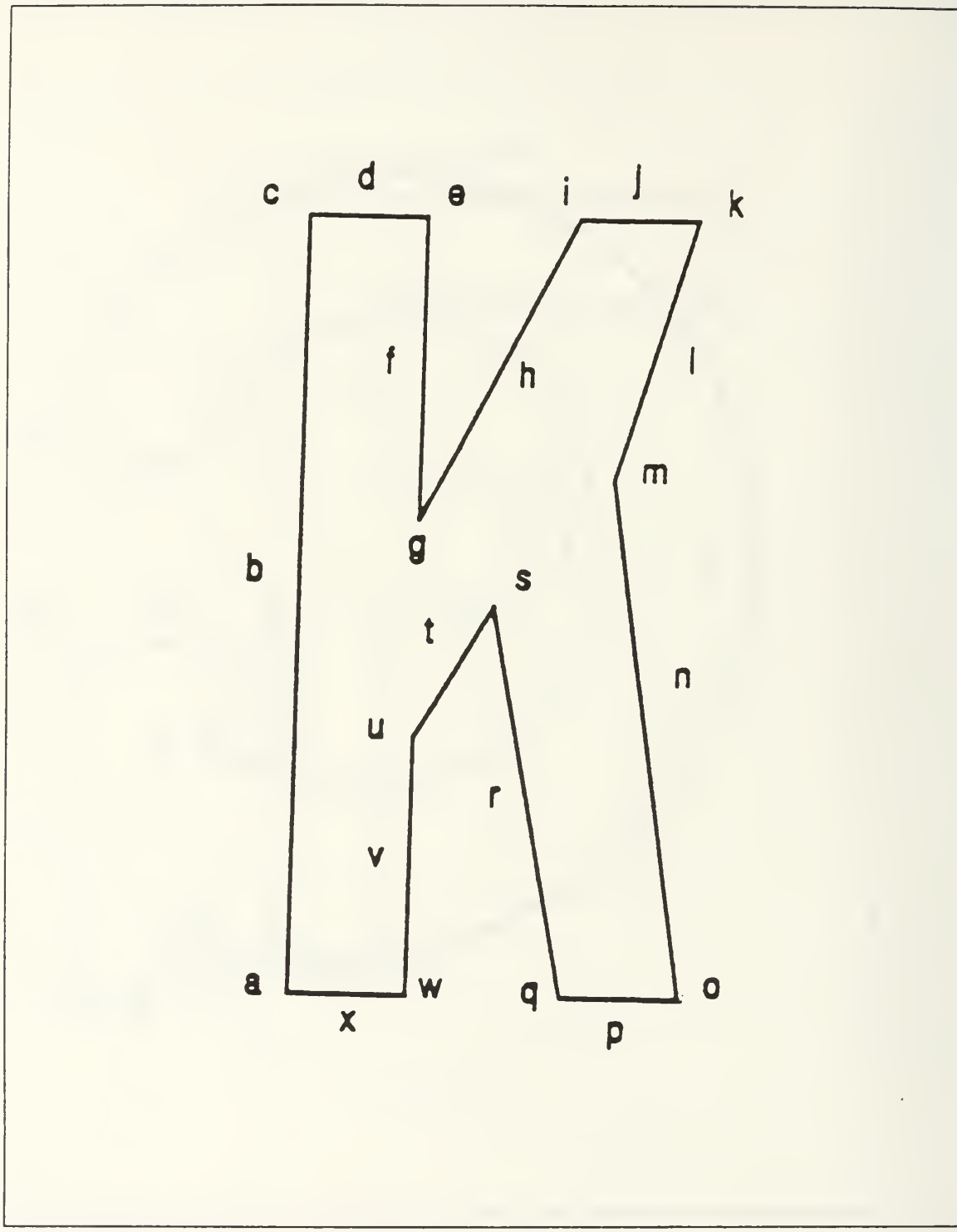
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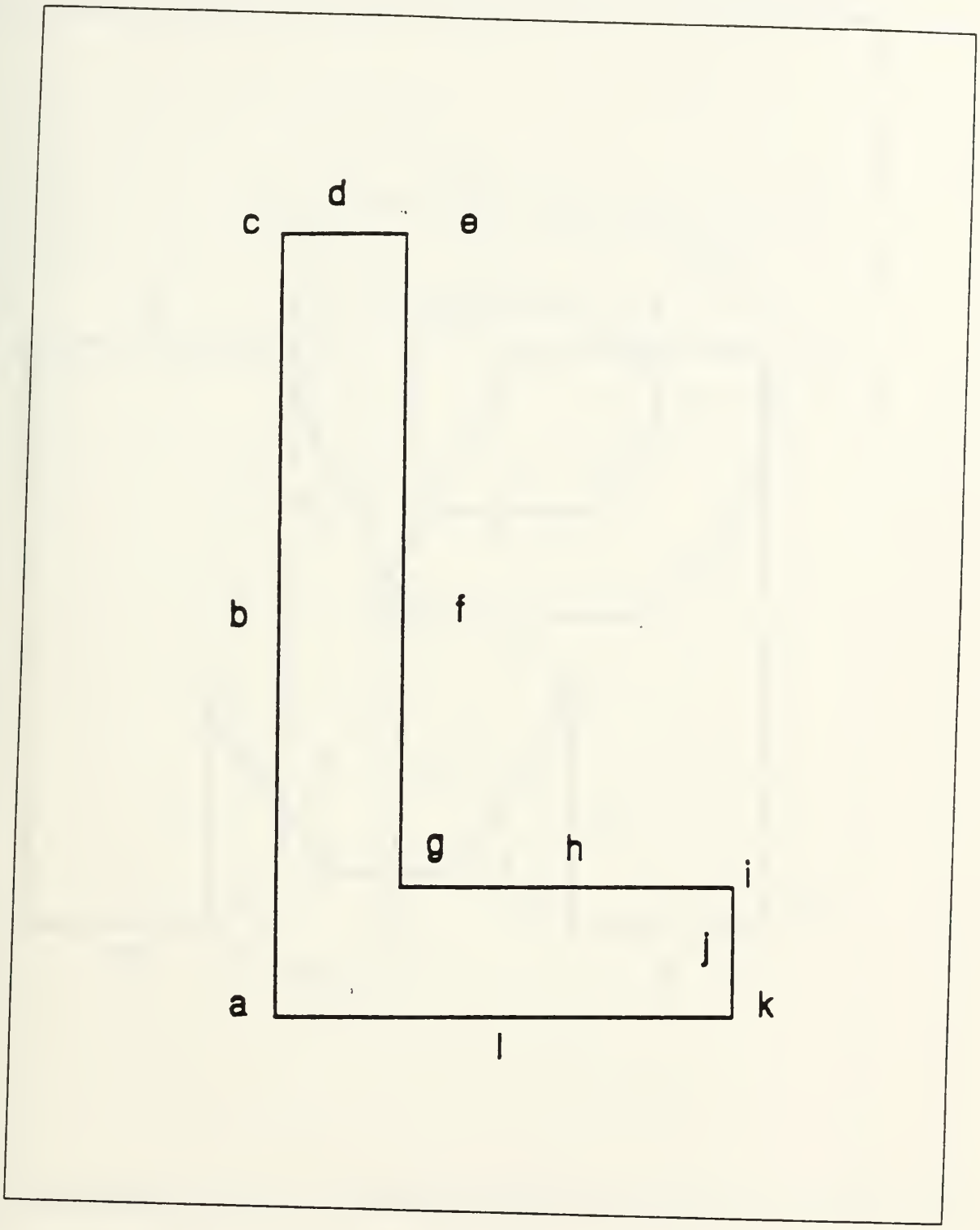
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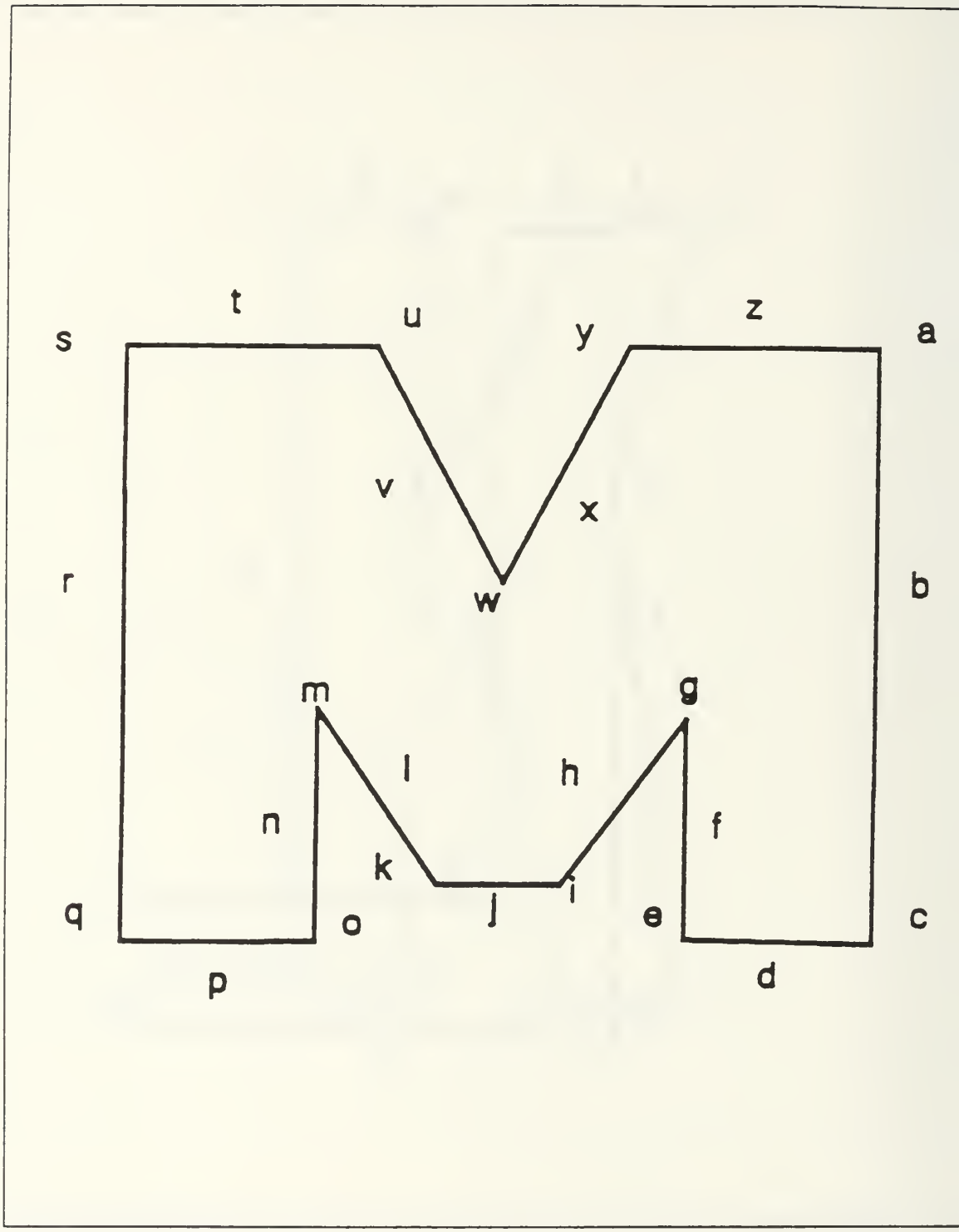
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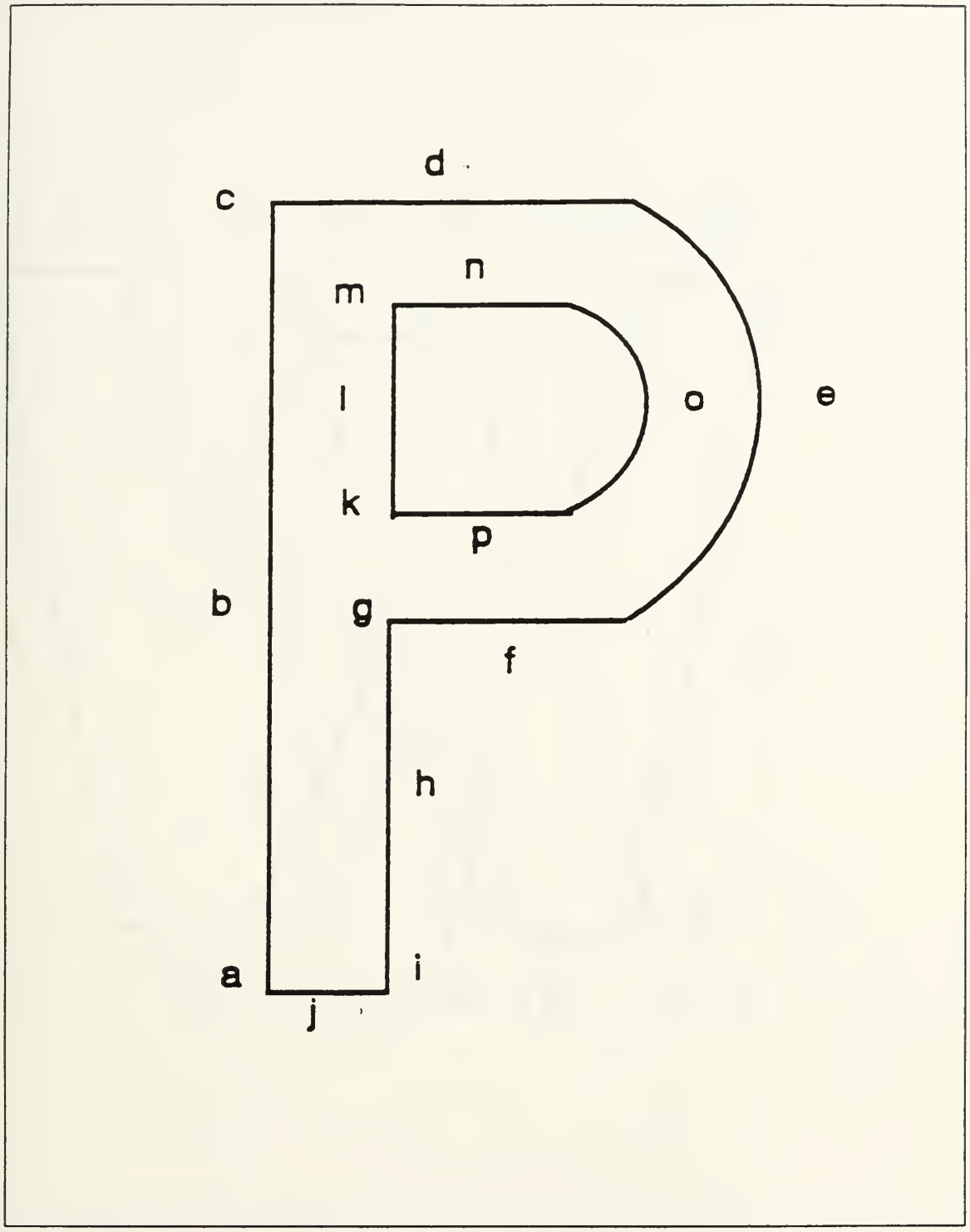
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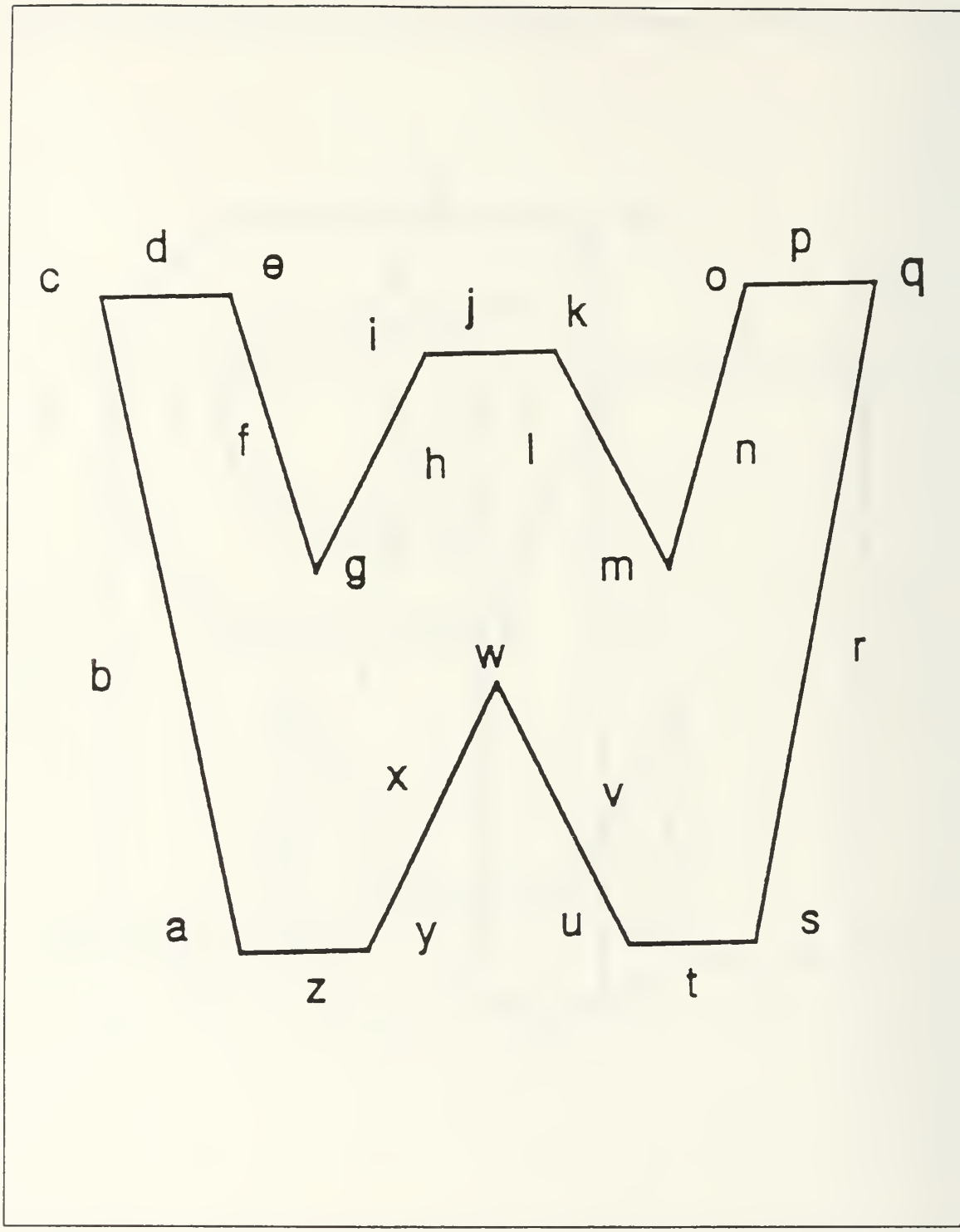
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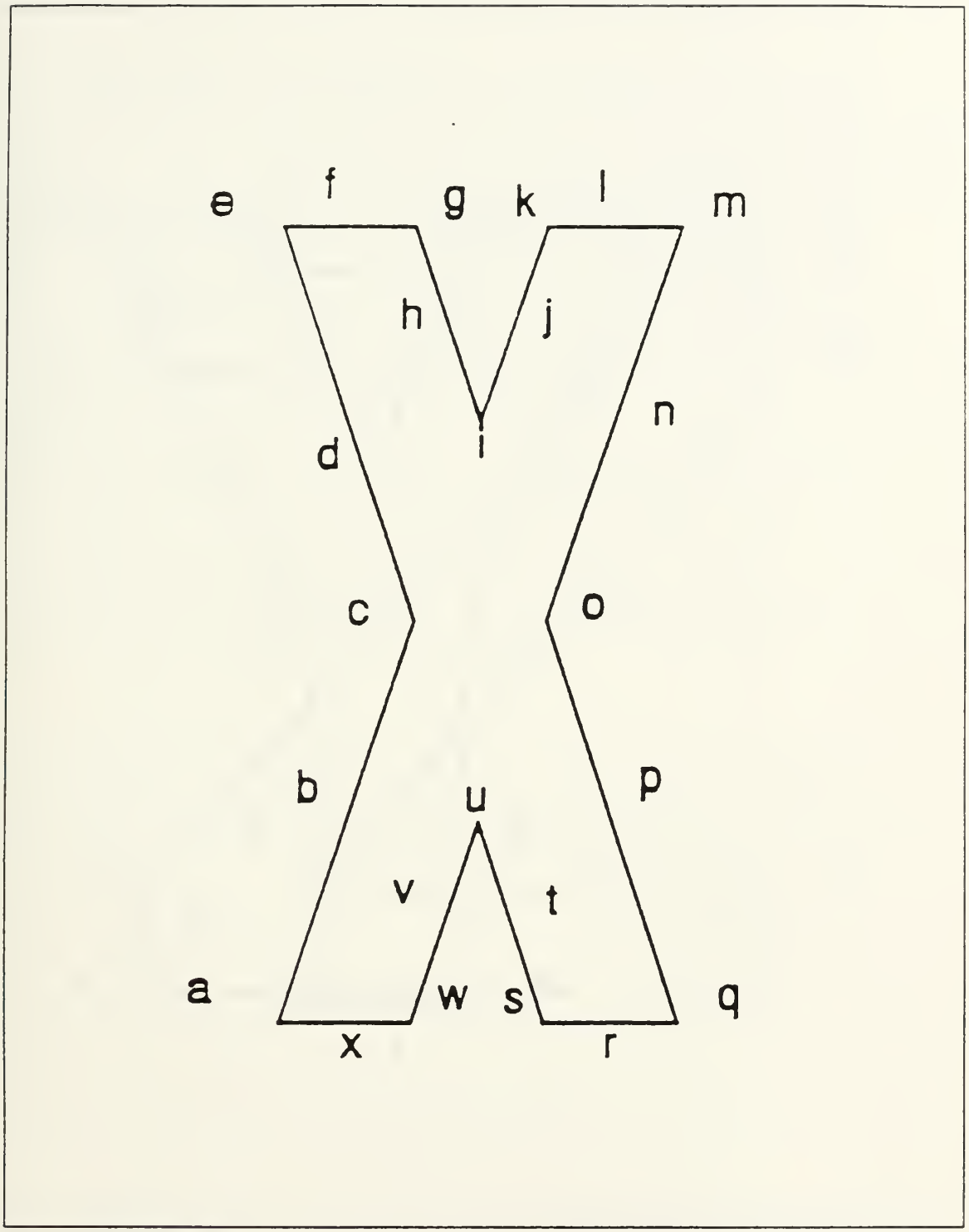
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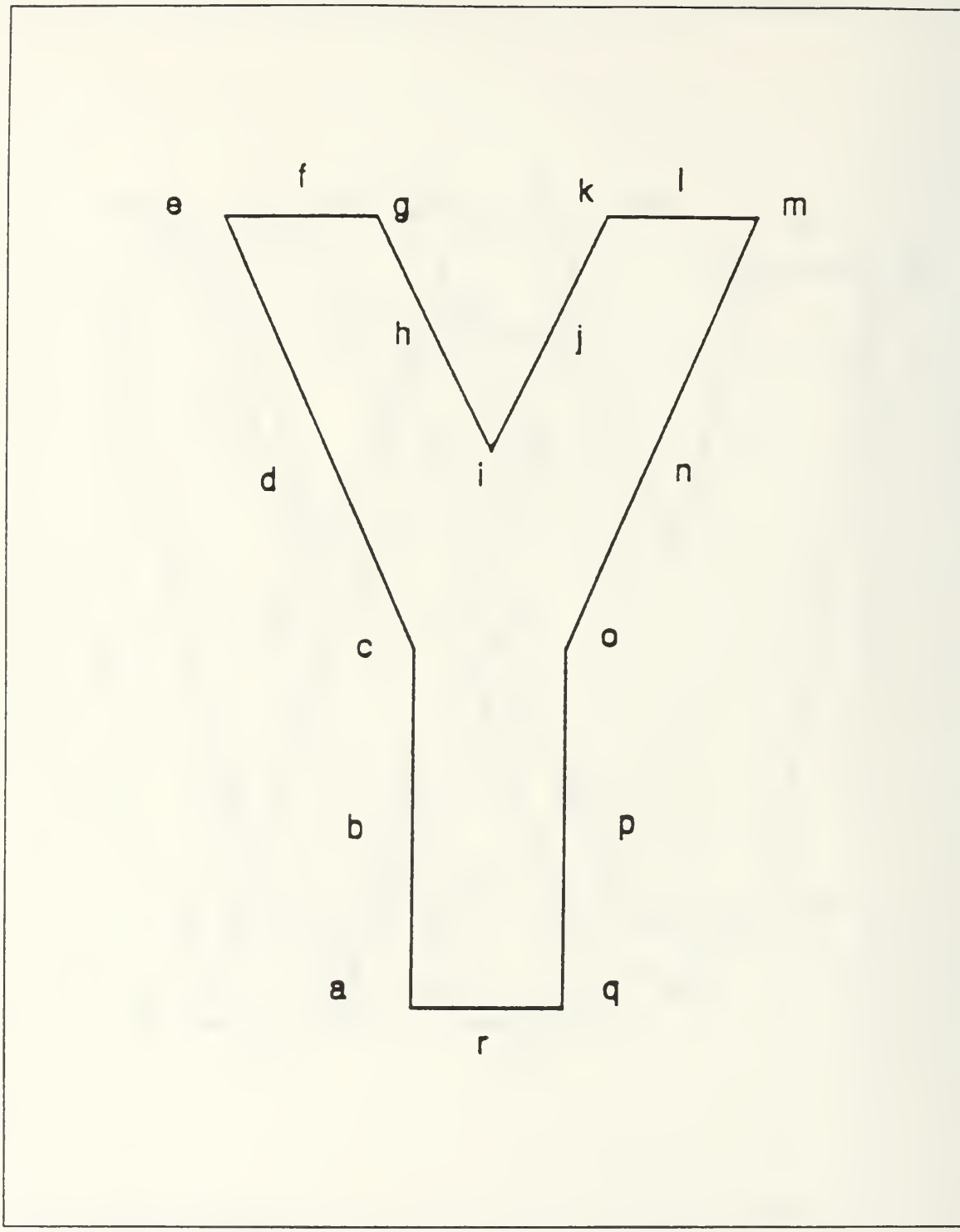
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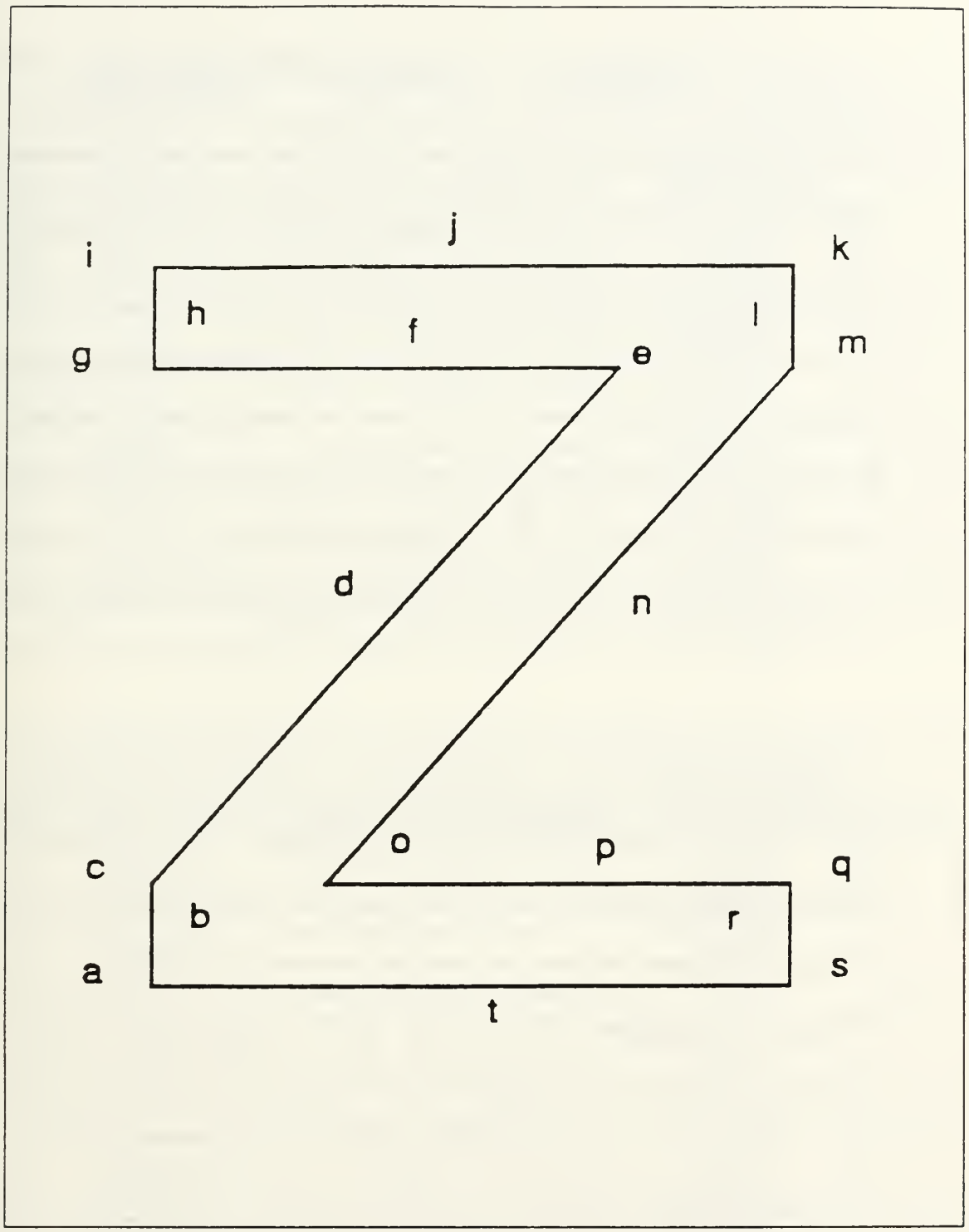
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APPENDIX C. EXPERIMENTAL RESULTS

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: C	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features	119	103	39		26	15
Total Features Explored	125	110	41		29	16
Sequence Ratio (%)	95.97	94.50	97.50		92.86	100.0
Time to Recognition (sec)	137	118	85		33	24
Recognition Rate (features sec)	0.912	0.932	0.482		0.879	0.667
Number of Reversals	25	21	6		13	8
Reversal Rate (reversals feature)	0.200	0.191	0.146		0.448	0.500

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: F	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features	111	81	49		59	44
Total Features Explored	119	870	52		65	47
Sequence Ratio (%)	94.07	93.10	96.08		92.19	95.65
Time to Recognition (sec)	101	84	76		69	53
Recognition Rate (features sec)	1.178	1.036	0.684		0.942	0.887
Number of Reversals	19	10	6		21	19
Reversal Rate (reversals feature)	0.160	0.115	0.115		0.323	0.404

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: G	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features	189	83	40	49		17
Total Features Explored	206	93	43	52		20
Sequence Ratio (%)	92.65	90.22	95.24	96.08		89.47
Time to Recognition (sec)	218	154	106	101		55
Recognition Rate (features sec)	0.945	0.604	0.406	0.515		0.364
Number of Reversals	39	24	9	4		6
Reversal Rate (reversals feature)	0.189	0.258	0.209	0.077		0.300

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: K	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features	129	116				50
Total Features Explored	135	122				51
Sequence Ratio (%)	96.27	95.87				100.0
Time to Recognition (sec)	127	138				40
Recognition Rate (features sec)	1.063	0.884				1.275
Number of Reversals	16	12				16
Reversal Rate (reversals feature)	0.119	0.098				0.314

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: L	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features	77	48		28	67	22
Total Features Explored	82	55		29	76	23
Sequence Ratio (%)	95.06	88.89		100.0	89.33	100.0
Time to Recognition (sec)	94	146		103	105	41
Recognition Rate (features sec)	0.872	0.377		0.282	0.724	0.561
Number of Reversals	21	14		1	30	8
Reversal Rate (reversals feature)	0.256	0.255		0.034	0.395	0.348

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: M	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features	33	83		52	91	44
Total Features Explored	41	90		57	117	57
Sequence Ratio (%)	82.50	93.26		92.86	78.45	78.57
Time to Recognition (sec)	46	189		105	130	54
Recognition Rate (features sec)	0.891	0.476		0.543	0.900	1.056
Number of Reversals	4	10		11	48	24
Reversal Rate (reversals feature)	0.098	0.111		0.193	0.410	0.421

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: **P**	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features		61	32	20		22
Total Features Explored		65	34	21		27
Sequence Ratio (%)		95.31	96.97	100.0		84.62
Time to Recognition (sec)		98	71	37		33
Recognition Rate (features sec)		0.663	0.479	0.568		0.818
Number of Reversals		8	10	5		6
Reversal Rate (reversals feature)		0.123	0.294	0.238		0.222

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: **W**	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features		65	57			
Total Features Explored		72	61			
Sequence Ratio (%)		91.55	95.00			
Time to Recognition (sec)		153	79			
Recognition Rate (features sec)		0.471	0.772			
Number of Reversals		11	18			
Reversal Rate (reversals feature)		0.153	0.295			

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: X	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features		92		64	68	37
Total Features Explored		99		66	70	40
Sequence Ratio (%)		93.88		98.46	98.55	92.31
Time to Recognition (sec)		92		150	51	55
Recognition Rate (features sec)		1.076		0.440	1.373	0.727
Number of Reversals		13		8	23	25
Reversal Rate (reversals feature)		0.131		0.121	0.329	0.625

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: Y	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features	143	96	79	26	30	57
Total Features Explored	146	99	82	27	37	67
Sequence Ratio (%)	98.62	97.96	97.53	100.0	83.33	86.36
Time to Recognition (sec)	128	94	99	44	32	60
Recognition Rate (features sec)	1.141	1.053	0.828	0.614	1.156	1.117
Number of Reversals	30	20	8	2	14	23
Reversal Rate (reversals feature)	0.205	0.202	0.098	0.074	0.378	0.343

MEASURE OF RECOGNITION	SUBJECT #1		SUBJECT #2		SUBJECT #3	
Letter: Z	Haptic	Comb	Haptic	Comb	Haptic	Comb
Sequential Features		63		47	79	62
Total Features Explored		66		48	85	66
Sequence Ratio (%)		96.92		100.0	94.05	95.38
Time to Recognition (sec)		82		82	60	82
Recognition Rate (features sec)		0.805		0.586	1.417	0.805
Number of Reversals		11		6	16	18
Reversal Rate (reversals feature)		0.167		0.125	0.188	0.273

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